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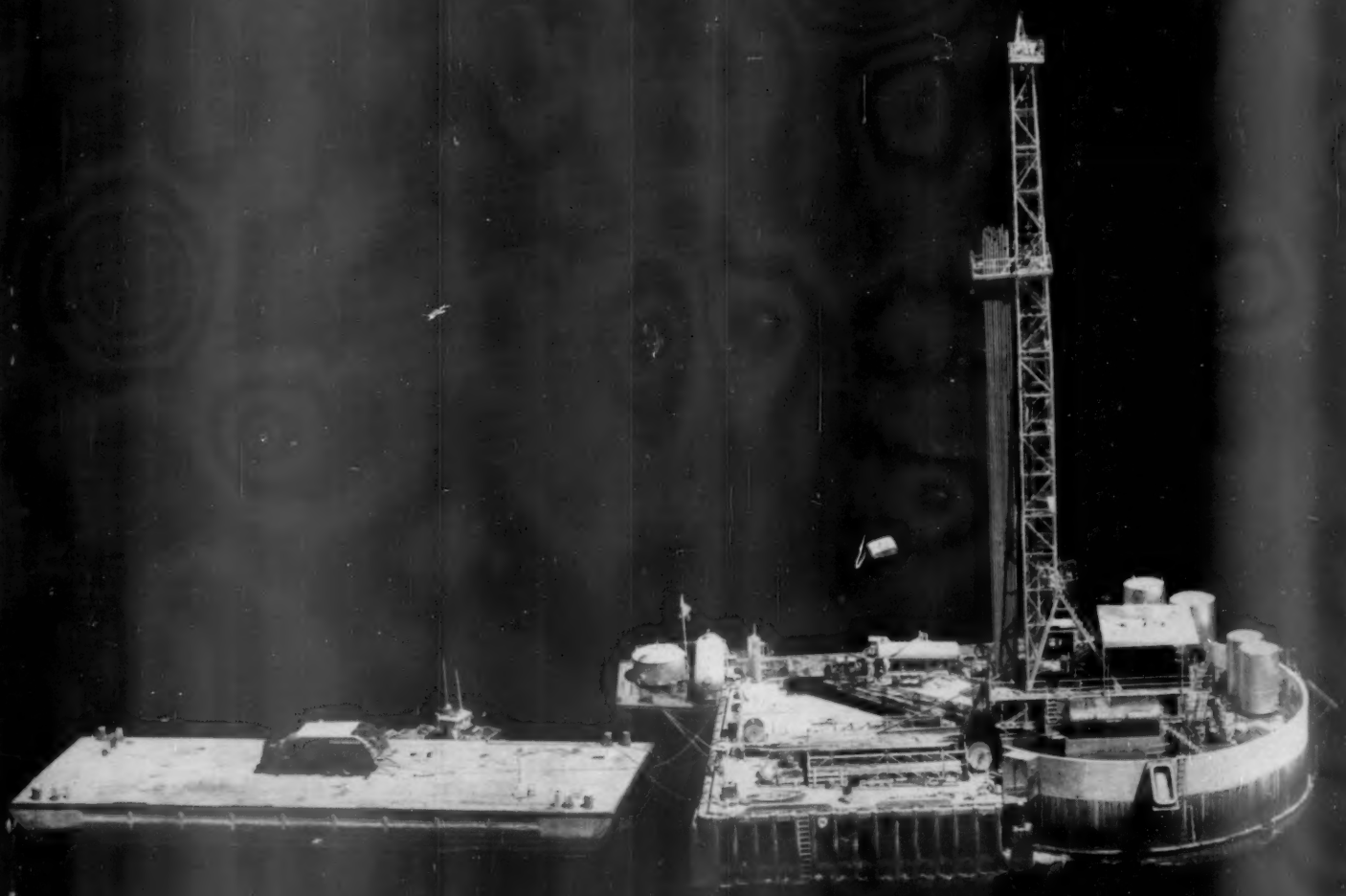

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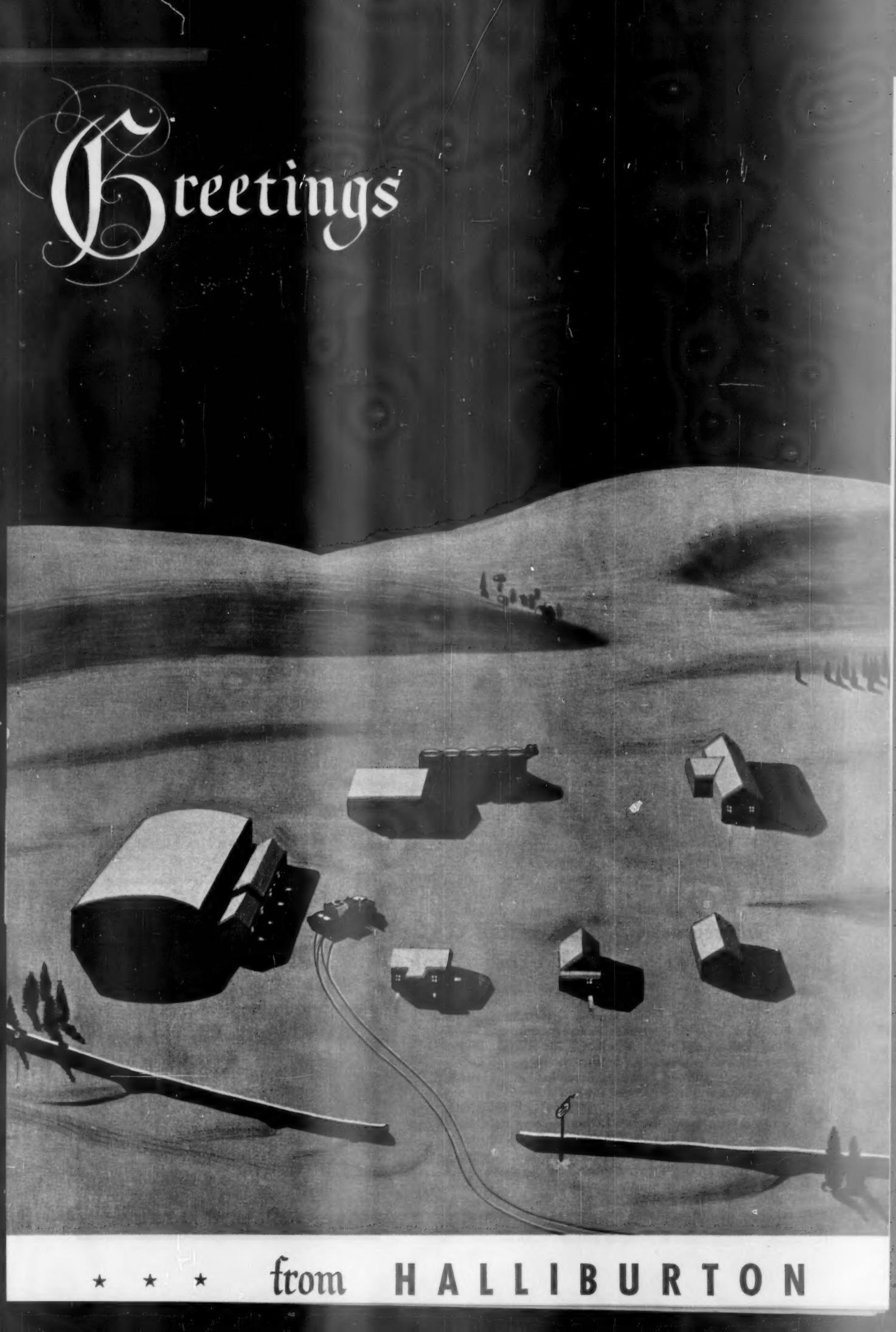
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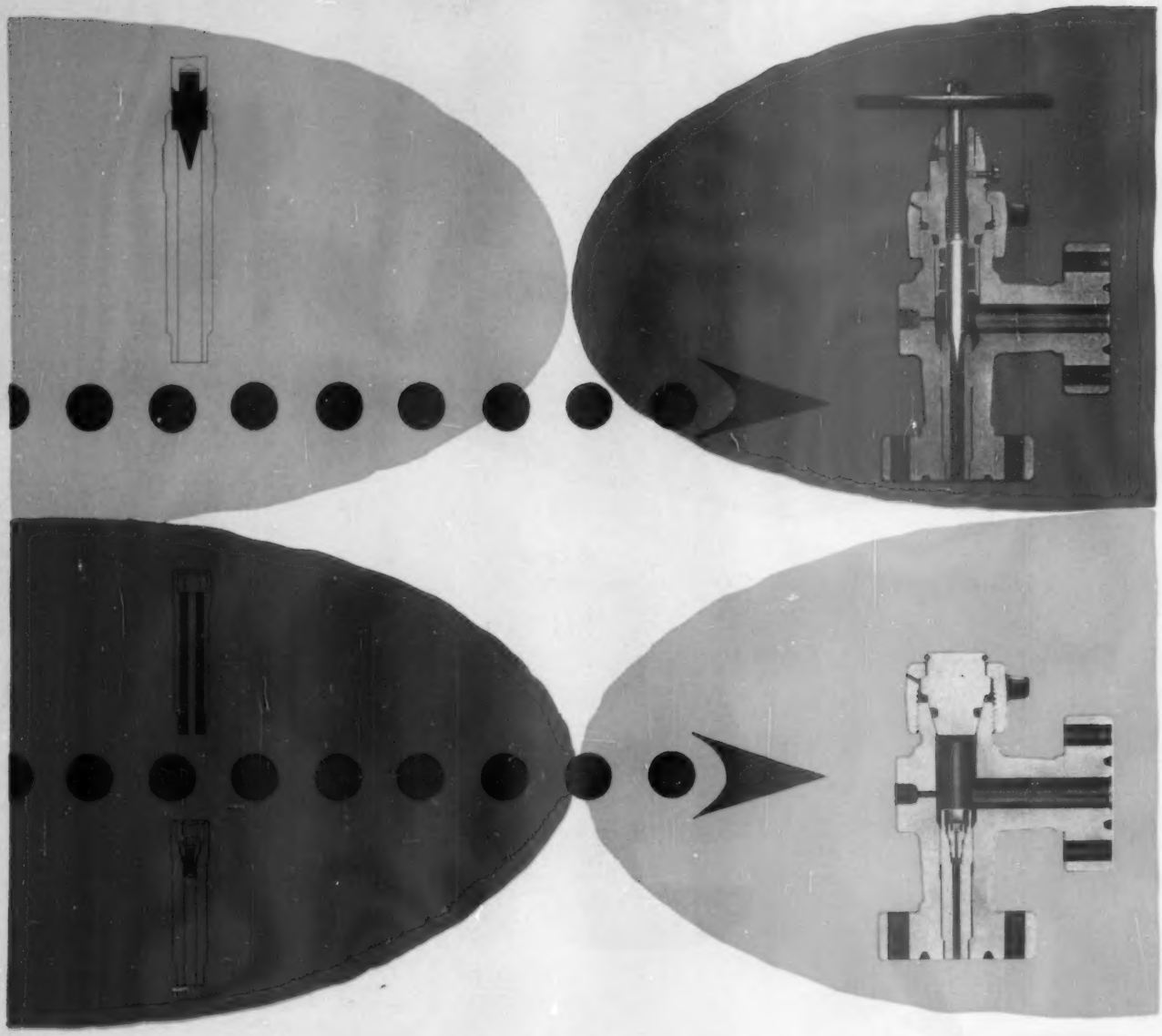

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This is the fourth of a series of editorials to be written on "What AIME Means to Me" by long-standing members of the Petroleum Branch, AIME.

EDITORIAL

WHAT AIME MEANS to ME

L. E. ELKINS
MEMBER AIME

STANOLIND OIL & GAS CO.
TULSA, OKLA.

We are often benefactors of an organization or a system without really appreciating its impact on our lives. In retrospect, I see how AIME has helped me professionally far more than I had realized. Briefly, AIME, both directly and indirectly, has enhanced most of my technological environment since my student days. This environment produced the mental tools, stimulated their use, and always pointed up the challenge that "there is a better way." AIME has also provided the opportunity to become acquainted with many leading petroleum engineers and geologists throughout the country.

Upon reflection, it becomes obvious that the least a petroleum engineer owes his profession is his membership in AIME. So much for generalities — here are some specifics.

AIME—The Educator

Remove from our engineering schools the literature published through AIME, blank out of the educator's mind the stimulation he has derived from AIME discussions, and education will be seriously handicapped. Thus, AIME enters the petroleum engineer's career at its foundation.

I remember very vividly an early experience in my engineering growth. A number of young engineers met weekly to discuss technical papers, chapters in petroleum engineering books, and articles relative to different aspects of petroleum engineering. Most of these had their origin in AIME. During one of these stimulating "digging into it" reviews, I received my first clear conception of fluid displacement mechanics. A once very hazy picture came into clear focus. It wasn't the particular discussion, or the one evening that clarified my thinking; it was the cumulative effect of many. This is just one illustration of the many ways that AIME makes its impact on engineers. Local AIME study groups offer this same opportunity. This stimulation and cross fertilization of ideas very likely have had more bearing on technical progress than we often recognize. This illustrates perhaps the principal reason for the existence of AIME.

AIME—The Standard Bearer

I often refer to AIME as the "standard-bearer of petroleum engineering technology." By and large, most of the papers which lead to the greatest advance in applied technology have first appeared in AIME forums. Their selection for a place in the *Transactions* heralds their general good caliber. They therefore become the building stones of technology. Quite often a paper may lose some of its direct value several years after its writing. In most cases, as it loses its direct value, it stimulates a succession of improvements. Thus, the standard of technology is steadily advanced — the book is never closed. Here again, all benefactors of petroleum engineering progress are very much indebted to AIME.

AIME, locally, regionally, and nationally, has provided me the opportunity to become acquainted with hundreds of petroleum engineers and geologists. Through many types of meetings planned by all geographical units of AIME, both professional and social contacts are provided. AIME would lose its savor if either type of contact were to suffer. Perhaps this professional-social bond contributes much to the high standard of ethics for which AIME members strive. Very few men will compromise ethics under the watchful eyes of "knowing" friends. Probably, after another 20 years in AIME, I will proclaim my AIME friends as the most treasured product of my membership. This could not be so were it not for the common desire to improve and apply technology.

AIME—The Spokesman

There is another satisfaction to be gained from AIME. Our institute is an organization of mineral technologists that can and does speak with influence on subjects within its scope. While avoiding politics, AIME does attempt to cast true light on issues that bear on the welfare of its membership and the mineral industry. For example, AIME joined with other technical societies in advising the War Manpower Commission on how to deal with the shortage of engineers. AIME also works with other societies in developing an accredited standard for engineering schools throughout the country. When representatives of the entire mineral industry speak on matters of this nature, they are heard. Sometimes a major controversy arises in some field of the mineral industry. AIME doesn't issue a proclamation as to what is right. Through the appropriate branch or division, it arranges a forum intended to bring out all sides of the question and let the members determine what they believe is correct and fair.

In appraising what AIME means to me, I have become aware of some deep satisfactions sometimes overlooked. Truly, AIME is the standard-bearer of technology and ethics for our profession. AIME stimulates an intense drive for high achievement for petroleum technologists and industry leaders.

It is sincerely hoped that others will take time occasionally to make a similar inventory. ★★★

FEATURE ARTICLE

OIL PRODUCTION — A CONTINUING CHALLENGE

JOHN R. SUMAN
MEMBER AIME

CONSULTANT
HOUSTON, TEX.

Rock Oil

In 1855 "rock oil" (petroleum seepages), which sold for 30 to 40 dollars a barrel, was used for medicinal purposes and widely advertised as "good for man or beast." We are all familiar with Col. Drake's "rock oil test" which was drilled near an "old oil spring" at Titusville, Pa., in 1859. After drilling into hard rock at 36 ft, "Drake's Folly" became the joke of the countryside. After many disappointments, the test struck oil at 69½ ft to open the first oil boom in the United States. Many wells were drilled in Pennsylvania, West Virginia, and New York during the next few years forcing the price of oil down to 10 to 20 cents per barrel.

Transportation and refining facilities, as well as markets (mostly for lighting and lubrication), increased steadily during the next 40 years. Consequently, oil prices were generally sufficiently low to encourage new uses for oil, and they were sufficiently high to provide a reasonable profit for the new industry.

The completion of the gusher at Spindletop in 1901 by Capt. Anthony F. Lucas ushered in a new era in production and marketing, with the use of fuel oil being expanded rapidly during the next 10 years. It is significant to note that the initial flow of the Lucas well was 75,000 to 100,000 B/D—equal to 50 per cent of the daily oil production in the United States during 1900. In 1901 Capt. Lucas presented a paper on the Spindletop discovery before the AIME. One of the interesting points in his discussion concerned formation evaluation.

Overproduction

Almost before the excitement of the Spindletop discovery had subsided, overproduction became a pressing problem. During the next 25 years, markets as well as daily oil production increased steadily. The ability of the United States to supply the fuel needs for the machines of war during World War I was considered to be an important factor in winning the war.

Following World War I, oil production continued to increase. In 1927, E. B. Reeser, president of Barnsdall Oil Co., wrote an article for the *Oil and Gas Journal* entitled, "A Challenge to the Oil Industry." The theme was: "Overproduction must be regulated by cooperation or government supervision. Leaders should develop a plan."

During the great depression of 1929-33, overproduction grew worse and prices dropped to ruinous levels. By Dec., 1931, the situation had reached a critical stage; enormous flush production of the East Texas and Oklahoma City fields could not be absorbed by an already oversaturated market. Governors of Texas and Oklahoma attempted to shut down and control production by military force and martial law. This chaotic situation was gradually ironed out somewhat by interested industry groups. In 1935, the Interstate Oil Compact Commission was formed for the purpose of determining means that should be taken to conserve oil and gas, and for promoting the enactment of legislation and enforcement by competing states.

World War II

Excess potential continued to be a problem until 1941, when the demand for oil skyrocketed during World War II. In addition to the oil and regular gasoline furnished for the vehicles of war, the industry met the challenge to furnish the tremendous demand for 100 octane gasoline and synthetic rubber. Supplying of fuel oil to power the huge United States Navy was in itself a real accomplishment.

At the beginning of the war, the OPA froze the price of oil at prewar levels. This freeze caught oil industry prices at an abnormally low point and, coupled with the shortage of steel, resulted in a relatively small oil field development program during the war. Although the industry emerged from the war with its producing reserves low, its plant facilities scrambled, and its markets disrupted, praise for oil industry contributions to the war effort was universal.

The transition from war to peace was made in a relatively short time without great difficulty. The post World War II period in the United States has been marked by greatly increased cost of finding oil and very large drilling programs which resulted in the finding of large reserves.

Technology Moves to Meet the Challenge

Probably the most serious and continuous problem which plagued the industry during the first quarter of

Paper presented at AIME Formation Evaluation Symposium in Houston on Oct. 27-28, 1955.

this century was the political hue and cry raised against "waste of natural resources." This situation created a particular impetus for scientific study of producing problems, including technologic improvement in reservoir control. It was one of the factors which motivated the formation of a number of technical organizations to study industry problems.

Technical Organizations

1. The Petroleum Div. of the Bureau of Mines, established in 1912, was the first organization in the history of the petroleum industry to make a concerted coordinated effort to understand the mechanics of oil production. From its inception it emphasized the importance of fundamental understanding of the physical processes involved in oil production and of the application of this knowledge to the development and exploitation of reservoirs. Near the end of World War I, field and laboratory studies were initiated by Bureau of Mines' engineers and scientists which were the precursors of our modern industrial production research and reservoir evaluation programs. Unquestionably the Bureau of Mines held the dominant position in the scientific study of reservoir behavior and control prior to 1927.

2. In 1914 the AIME set up a "Committee on Petroleum" with Capt. Anthony Lucas as chairman and began to hold annual forums for discussions on technical problems of the oil industry.

3. In Feb., 1917, the Southwestern Association of Petroleum Geologists (changed to American Association of Petroleum Geologists in 1918) was formed for the promotion of the science of petroleum and gas.

4. In 1919 the American Petroleum Institute was organized and soon became an active force in the promotion of technological developments within the industry.

Federal Oil Conservation Board

When the Federal Oil Conservation Board was appointed by President Coolidge in Dec., 1924, the API was officially invited to assist the Conservation Board in assembling data and reaching conclusions in regard to oil conservation measures. An initial API committee of 11 members was appointed to prepare the industry's case; however, final recommendations of this committee were somewhat negative because of their suspicion of the motives of the Conservation Board.

As the work of the Conservation Board continued along constructive lines, the API's attitude changed and a new committee with E. W. Marland, president of the Marland Oil Co., as chairman was appointed to work with the Conservation Board. Members of this committee were Henry McGraw, William S. Farish, Thomas A. O'Donnell, Sid H. Keoughan, J. Edgar Pew, and L. P. St. Clair. The Marland Committee was composed largely of non-technical men, and it was soon found that a technical working group was needed to solve some of the more complex and difficult technical problems facing the industry. Accordingly, regional committees were organized with M. E. Lombardi, chairman for the Pacific Coast; Max W. Ball, chairman for the Rocky Mountain area; John R. Suman, chairman for Texas and Louisiana; W. P. Haseman, chairman for Kansas and Oklahoma; and Earl Oliver, general secretary. The Marland Committee reported its findings to the API in Dec., 1927. Following are some of the resolutions proposed by the Marland Committee:

"Resolved that . . . the industry adopt every reasonable and practical means to effect the conservation of natural gas in oil bearing formations in the interest of economies in production costs, increased ultimate recovery, and in the interest of conserving our supplies of petroleum, and to the end that proper recognition of the correlative rights of land owners and lease owners in a given pool might be attained.

"Resolved that the American Petroleum Institute encourage the cooperative development of oil pools wherever found under diversified ownership, as the best means of effecting the greatest economies in production of oil, and the best means of conserving our petroleum resources; and that to this end the Institute should encourage passage of the necessary state legislation to permit cooperative development of oil pools . . .

"Resolved that the Institute should impress upon its members in the several states, where oil is being produced, the need for state legislation or other state regulatory measures to permit and require the producers of oil and gas . . . to adopt measures to prevent the waste of natural gas found in oil sands."

The findings of the Marland Committee were assembled by H. C. Miller of the Bureau of Mines and published in 1929 in a book entitled *Function of Natural Gas in the Production of Oil*, under joint sponsorship of the U. S. Bureau of Mines and the API.

Some Significant Industry Developments 1901 - 1955

From 1901 until 1951 many significant developments took place in the oil industry. Some of them are listed below.

In 1903 Union of California used cement in California oil wells to shut off water.

By 1920, a technical development of formation evaluation included use of strip formation logs for correlation, and peg models. Coring was becoming widespread. One of the earliest types of coring equipment used in the Southwest was the "poor boy" or "Texas" core barrel. This consisted of a short piece of pipe with V-shaped teeth cut on its lower end and run on bottom of drill pipe. After a core was cut, excess weight was set down on the pipe to bend the V-shaped teeth inward, thus holding the core in place.

By 1921 core analyses and drill-stem tests were in general use, and Elliot's core barrel was being employed. This core barrel, having a stationary inner barrel which greatly increased core recovery, is considered to be one of the most important developments of the period.

Search for Oil

Although studies of subsurface strata of the earth had been made by physical measurements on the surface much earlier, it was not until after the close of World War I that suitable apparatus was developed to carry on such studies in the search for oil.

1. In 1921 or 1922 a group of Germans (L. Mintrop, et al), having developed portable refraction seismic equipment, introduced seismograph crews into Mexico and the United States. During this same period Anglo-Persian and Dutch Shell groups were making trial surveys with the torsion balance. In Dec., 1922, torsion balance instruments were first introduced into the Gulf Coast region, the first work being carried out (according to DeGolyer) at Spindletop.

2. Although earlier work had been done with the refraction seismograph in Mexico and the Mid-Con-

tinent area of the U.S., it was not until March, 1924, that work of this type was done in the Gulf Coast. The first crew was obtained from Seismos Co. (Mintrop) and was under the general direction of Alexander Deussen for Marland Oil Co.

3. During the period 1924-1930 an intensive and highly successful campaign of searching for shallow salt domes, varying from a few hundred to 5,000 ft in depth, was carried on by use of refraction seismograph and torsion balance instruments.

4. About the same time the seismic and torsion balance systems were being introduced, the magnetometer (also a German development) was put into use. The results obtained by the magnetic method were not as revealing and not nearly as spectacular as those shown by the gravity and seismic methods. The magnetometer, however, proved to be a useful instrument for exploration in regional type studies, particularly to indicate special types of structure such as serpentine plugs.

5. J. C. Karcher began work on the reflection seismic method as early as 1919, and some field work was done in Oklahoma in 1921. However, it was not until 1928 that the method was sufficiently perfected to be put into commercial use in Oklahoma. The reflection seismic method spread rapidly, and by 1931 it had replaced the refraction method almost completely. A very active campaign of reflection work began in the Gulf Coast region in 1931.

6. As a culmination of several years of research effort, principally by O. H. Truman, the first successful gravity meter was built by Humble in early 1931. After a period of development to make the instrument more field worthy, the lighter and faster gravity meter replaced the torsion balance in the conduct of gravity surveys.

Other Significant Developments

In 1929, Marcel and Conrad Schlumberger brought their new electric logging tool over from France.

In the lean early 30's there was an accelerated trend toward greater portability of rotary rig equipment.

One of the earliest uses of directional drilling in the Southwest was Humble's killing of a wild well in Conroe in Jan., 1934, by drilling within 30 ft of the bottom of the wild well and pumping in water to kill it. To the best of my knowledge, this was the first successful effort to kill a cratered oil well by this procedure.

Development in radioactivity logging began in the late 30's and was in commercial use by 1940.

Reservoir Engineering

The growth of reservoir engineering during the past 25 years has probably been the most important industry development during the past 100 years. This new science has caused a fundamental shift to formation or reservoir evaluation instead of thinking about individual well behavior. Some of the pioneers in forming currently accepted basic reservoir concepts were: Stewart Coleman, H. D. Wilde, Jr., T. V. Moore, S. E. Buckley, M. C. Leverett, Morris Muskat, Ralph Schilthuis, A. F. Van Everdingen, H. G. Botset, and R. D. Wyckoff.

For a number of years a fundamental mathematical challenge to reservoir engineers has been the derivation of equations that describe the flow of reservoir fluid systems and the development of practical solutions for such equations. Basic equations were developed to predict the rate of production and ultimate recovery of each of the fluids from a given reservoir under natural or artifically imposed conditions. Undoubtedly the development of electric analog computing machines, including the oil pool electric analyzer by Carter Oil Co. in 1942, was a major reservoir engineering achievement. Within recent years the use of digital computing machines has made it possible to perform mathematical operations at rates hundreds of times those possible with a desk calculator. These machines have enabled the reservoir engineer to effect more complete (and, therefore, more reliable) solutions of problems previously considered insoluble because of the magnitude of the computation work involved.

Brilliant Scientific Achievement

Although the science of reservoir engineering is not complete today, the advances in knowledge of reservoir behavior and control which emanated from the many competing companies of the industry between 1927 and World War II constitute a record of brilliant scientific achievement. The increased recovery of oil which has resulted is an excellent example of the progress that can be made by private enterprise operating in a climate of economic freedom.

It is worthy of note that this era included one of the most serious economic depressions in the history of the United States, a condition that might have been expected to discourage industrial research.

Shortage of Engineers

Unfortunately, one of the principal problems facing the industry today is the shortage of engineers and experienced teachers to train additional engineers. Current registration of engineers in the various colleges indicates that the number of engineering graduates will increase considerably during the next few years. In the meantime, maximum benefits from available talent can be realized by assigning engineers to strictly engineering duties, rather than requiring them to perform semiclerical and other non-technical tasks.

There does not appear to be an immediate solution to the instructor shortage, however. Fewer technical graduates are entering the teaching profession because positions with industry are more attractive financially. Some companies are attempting to alleviate this situation with direct grants to the universities and colleges, retaining faculty members as consultants, and making part-time employment available. Still, it appears that the present help for colleges by industry is insufficient. New ways should be found to insure that adequate competent instructors are available to properly train engineers for the industry.

Conclusions

It is obvious that the great advance made by the oil industry could not have been possible without the wonderful cooperative spirit existing over the years between the oil producers, the service companies, the governmental agencies such as the Bureau of Mines and The Texas Railroad Commission, and the many industry technical groups including the AIME, API, and AAPG, plus the continued active support by the many excellent universities and colleges.

This Formation Evaluation Symposium is a fine example of such cooperation, the system of free enterprise in action, with the entire Symposium being sponsored by the University of Houston and the AIME. With this type of cooperation, the industry cannot fail to continue to move forward—under forced feed of rapid technical advances. ★★★

FIRST PACIFIC COAST PERMANENT DRILLING ISLAND MODIFIED to ALLOW DRILLING of 70 WELLS

E. E. PYLES
ASSOCIATE MEMBER AIME

MONTEREY OIL CO.
LOS ANGELES, CALIF.

The first permanent drilling island constructed on the Pacific Coast is now being modified to provide surface locations for the drilling of a total of 70 wells. The small circular Monterey Oil Co.-The Texas Co. filled island, 1½ miles offshore from Seal Beach, was originally designed for the drilling of only three wells. Now, through the construction of a raised floor to provide additional cellars, this small island is expected to provide adequate surface drilling sites from which to develop the lease.

When this modification has been completed, about the end of this year, the little island will provide probably the densest concentration of drilling sites anywhere in the world.

The circular island is 75 ft in diameter and is located in 45 ft of water. A rectangular wharf 74 ft by 51 ft extends shoreward from the island. A group of four pipelines connects the island to a separation and shipping center onshore. Nine wells have been drilled from the island to date, and the tenth one is now being drilled.

The outer rim of the island is formed of interlocking sheet steel piling driven into the ocean floor to a depth of 15 to 20 ft. The interior is filled with rock and sand. A series of parallel reinforced concrete beams across the island carries the working load. Each beam is supported by a line of wood piling. The reinforced concrete floor rests on the beams and sand fill. The construction of the raised floor above the original concrete floor is now in progress. Through this addition the island, which was once considered supplemental only, will become a very valuable surface property from which to develop the extensive oil reservoir. The operators have spent approximately $750,000 in connection with island construction.

Early History of the Lease

In 1944 the Marine Exploration Co., one of the predecessors in interest of Monterey Oil Co. and The Texas Co., obtained rights to drill for oil offshore at Seal Beach by obtaining a state lease which was the predecessor of the present State Lease PRC 186.1. This lease begins at the Seal Beach shoreline and extends 3 miles seaward. The drilling of the first two wells was done from a land location in the City of Long Beach, County of Los Angeles, 2,500 ft inland from the water's edge.

The first well drilled from the land site was unsuccessful. The second well was also non-productive, but was redrilled to a location 9,271 ft seaward from the surface location and bottomed in the state lease, which is in Orange County. The deviation of this well reached 80 degrees from vertical and the drilled depth was 12,187 ft. The perforated interval was from 11,447 ft to 11,890 ft, but because of the very high deviation from vertical the pump was run to only 7,142 ft. The well was completed in Nov., 1948, pumping 41 BOPD.

In a number of respects this well was unique. It produced oil from a greater distance seaward than any California well so far drilled. At present, after five years' production, it still yields 25 BOPD of 26° API gravity oil.

While the second well was being drilled from the location on shore, the California State Lands Commission by resolution instructed the company that all future

Fig. 1 — Members of the Southern California Petroleum Section of AIME view The Monterey Oil Co.-The Texas Co. filled island during a recent field trip.

wells drilled into this state lease be drilled from a filled island offshore.

Building of the Island

The results of the second well justified further exploration of the leased area and, therefore, the operators decided to build a filled island on the lease in accordance with the State Land Commission's orders. Legal entanglements prevented the issuance of a permit by the United States Engineers until 1952. Finally, the permit was granted and the building of the island was started.

The location of the island was chosen so that when enlarged later it would fall in line with the proposed extension of the Long Beach breakwater. Also, the island would present no obstruction to shipping and would be protected from heavy seas by the breakwater at the selected location.

The island was designed by Capt. George F. Nicholson of Long Beach to provide surface locations for the drilling of three wells. Sand was built up into a mound by a dredge, and then wood piles and the conductors for three wells were driven. At this point the work was stopped by injunction resulting from a claim by the City of Seal Beach to jurisdiction of offshore land to the 3-mile limit, and an ordinance preventing drilling in the City of Seal Beach. In a final decision, the California appellate courts eventually ruled that the City of Seal Beach had no jurisdiction over the tide and submerged lands owned by the state. This litigation caused a delay of 14 months, during which time the partially completed island was maintained at a cost of nearly $100,000.

The driving of the wood piles was completed and outside spuds were driven to support the circular beams, or waling, around the island. This waling was used as a guide for the driving of interlocking sheet steel piling, which was driven to refusal, and which formed the circular shell of the island.

The space between the piling and three conductor pipes and the circular shell was then filled with 6,000 tons of small Catalina rock and 6,500 tons of sand. Gunited wood piling was then driven for the 74 ft by 51 ft rectangular wharf. Protection on the outside of the shell was provided by placing 14,600 tons of rip-rap around the shell to within 10 ft of water level. The rip-rap slopes outward to a distance of 45 ft from the island. Rip-rap was also placed under the wharf, but only to within 26 ft of the water level.

Seven reinforced concrete beams were poured, supported by the rows of wood piling. The concrete floor for the island and wharf was poured simultaneously. The floor thickness varies from 6 in. to 9 in. Space was provided for a cellar 6 ft deep by 8 ft wide and 11 ft long, within which were the conductor pipes for the three wells; space was also allowed for a 12 × 12 × 12 ft mud pit and sump. The concrete floor was built with a slight slope so that liquids on the floor would drain toward the sump.

A concrete wall extending 8 ft above the floor level was built around the island except on the wharf side, where it was reduced to a curbing. This wall was to protect the crew from wind and spray during rough weather.

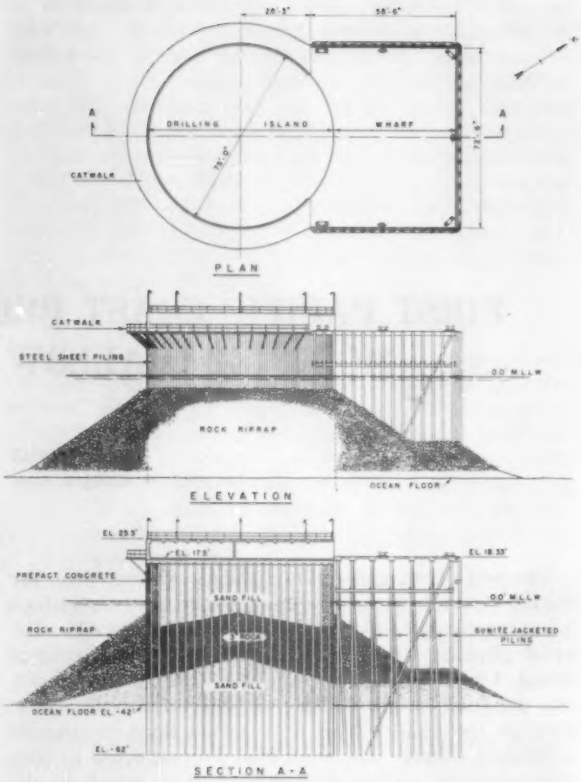

Fig. 2 — Plan and cross-sectional drawings of The Monterey Oil Co.-The Texas Co. filled island.

The island was so designed that all the major loads to be carried would be borne by reinforced concrete beams, which were, in turn, supported by rows of wood piling. The type of design selected included such large factors of safety that there was no special need for concern about earthquake and storm loads on the structure as a whole. A sandy ocean bottom and convenient source of rock at Catalina Island made the design economical as well as sturdy. The island is capable of lasting 50 or more years, as may be required to produce the lease to an economic limit.

Equipment and Facilities on the Island

The drilling rig was specially designed to operate in the restricted space available on the island. Before moving any drilling equipment to the island, the drilling contractor laid out an area the exact dimensions of the island working area, and assembled and unitized the rig within this area. Reinforced mud tanks were set under the elevated regular rig substructure, thus providing mud storage without using additional floor space. The additional height of the rig floor also provided room for mounting the mud pumps under the drilling engines. For further testing, the rig was moved to a Monterey Oil Co. lease and used to drill a well duplicating conditions anticipated on the island.

Fig. 3 — Laying of the submarine pipeline cluster. Four pipelines are bound together to form the cluster.

The island has tanks for fresh water and fuel oil. Drilling mud was mixed on shore and taken to the island in barges; this was simpler and cheaper than separately transporting the dry materials and water. Waste mud was barged to shore for disposal.

Cementing operations are conducted from cement trucks on barges; the slurry is pumped through leak-proof hoses to connections at the casing head. Well logging is also handled from barge-borne equipment. Extreme care is exercised to assure that no waste material of any kind, no matter how clean, is permitted to get into the ocean.

Crew changes are made by boat from the Seal Beach pier on regular eight-hour shifts.

The island has emergency housing for the members of the drilling crew in the event of water so rough as to make their departure from the island inadvisable. An office and emergency supply room is located under the elevated change room, and contains a desk, a telephone tied into the Long Beach exchange by a submarine cable, stove, sink, refrigerator, folding bunks for 12 persons and emergency food supplies for 12 persons for 48 hours.

For fire protection there are power pumps and chemical equipment, hoses, fog nozzles, and portable extinguishers. There is also a barge mounted pump and monitor. Life jackets are readily available and life rafts are placed so that they may be quickly released from either the top or bottom of the several escape ladders. The safety line from the derrick is attached to the outer corner of the wharf. Foghorns and lights are available and are used as required by Coast Guard regulations.

The Submarine Pipeline

During the drilling and completion of the first six wells there were no pipelines between the island and the shore, and the wells were cleaned up and tested into a barge. The crude oil produced during this completion procedure was barged to Wilmington. The reserve blocked out by the first six wells was of sufficient magnitude to economically justify the construction of submarine pipelines from the island to a separation and shipping center on shore.

Pipeline construction was started in April, 1955. The work consisted of the installation of one 8-in. and three 3-in. somastic coated steel pipes along with one 1.275-in. armored electrical communication cable. All were placed parallel in a common trench from the drilling island approximately 8,100 ft offshore to the tank battery approximately 2,500 ft inland. The lines and cable on shore were laid parallel on the bottom of a trench. For the submarine section of the line, the lines were welded on shore into sections approximately 750 ft long, the joints X-rayed, and the assembled lines pressure tested and coated. All three lines and the multiconductor electric cable were banded together and then pulled out to sea. Another cluster 750 ft long was then added, and this procedure was continued until the line reached the island 8,100 ft offshore. The cluster of lines was then embedded by means of a hydraulic jetting machine. The pipe on land and out to a water depth of 15 ft was covered a minimum of 3 ft. Cover from the 15 ft water depth to the island was 5 ft minimum, in order to protect the line from dragging anchors of large ships. The first oil was shipped through the line in July, 1955.

The commingled oil and gas from the wells is shipped to shore through the 8-in. line, which has a capacity of 10,000 BOPD. The oil and gas are separated on shore. The individual wells are tested by producing through a gas-separator on the island, from which the oil is delivered to shore through one of the 3-in. lines to a tank for gauging and the gas is metered out of the separator. The two remaining 3-in. lines are available for delivery of mud, fuel oil, fresh water, or other use as required. There is no crude oil storage on the island.

Present Modification Program

The three originally-planned wells from the island were successfully completed. Modifications to the cellar permitted the drilling of four more wells. Then, by using the mud pit as a cellar, three more locations were possible. The tenth well is now being drilled from the island. The experimental island had proven a success, but had reached its capacity in cellar space to accommodate the required wellhead equipment and flow lines.

The original plans, which provided for the building of a 600 ft square island, were again studied. Construc-

Fig. 4 — Construction work is now proceeding on a raised floor which will provide additional cellar space. This modification of the island will permit the drilling of an additional 60 wells.

tion of such an island would require about two years. The original island was satisfactory except for the lack of the necessary cellar room. It was, therefore, decided to modify the original island.

As the first step, 60 additional conductors were driven, with approximately 5 ft between conductors. Also, added strength and permanence was given to the island by removing the sand from within the steel shell of the island, replacing it with gravel, and grouting this gravel with cement through pipe driven into the gravel to a depth of about 20 ft. This was done in a ring 4 ft wide adjacent to the outer steel sheath, thus forming a concrete wall inside of the interlocking sheet piling.

Work is now in progress on the construction of a new working floor which will be 9 ft above the former working surface of the land. The space between the old floor and the new floor will provide the cellar space required for the drilling of the additional 60 wells.

Conclusion

The experience that has been developed through the preliminary stage of California's first real offshore drilling program is of benefit not only to Monterey Oil Co. and The Texas Co., but to the California petroleum industry generally. The new California law makes offshore exploration more attractive and the other companies may be able to profit by the knowledge gained through this early development. Although the new California law no longer requires that offshore drilling be done from filled islands, building of this type of structure may still be the most practical under certain conditions.

The Monterey-Texas interests are pleased to have been of service to the industry by helping to establish legal precedents concerning offshore drilling and by pioneering the building of the first Pacific Coast offshore drilling island. ★★★

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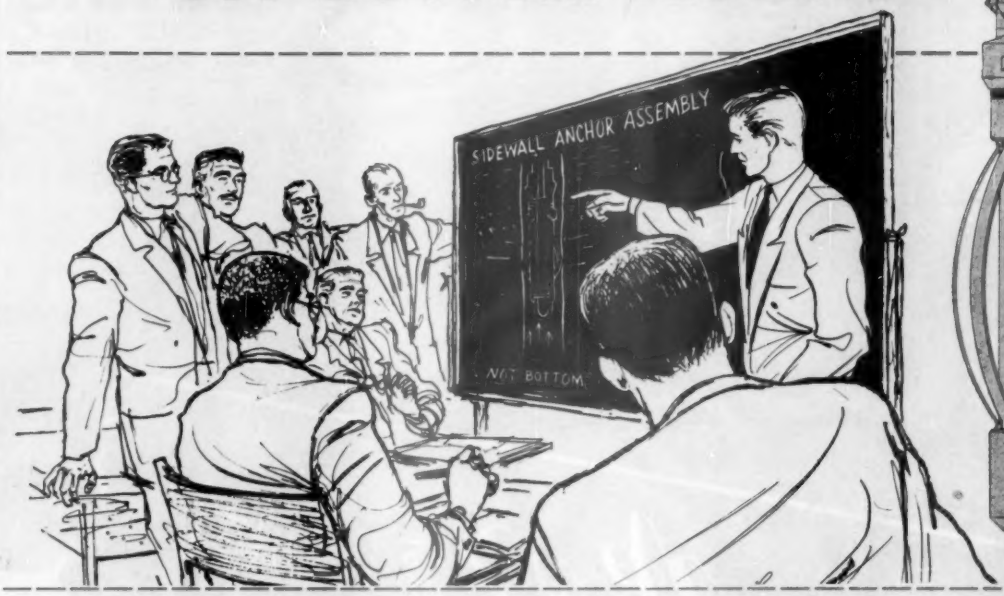

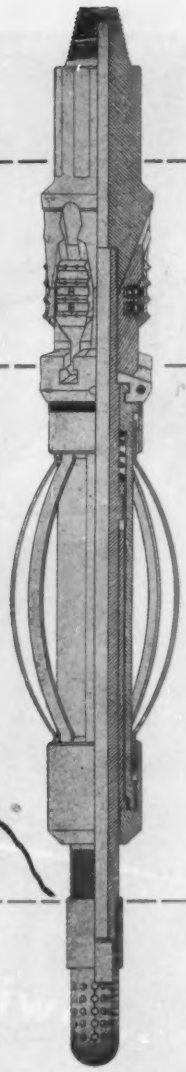

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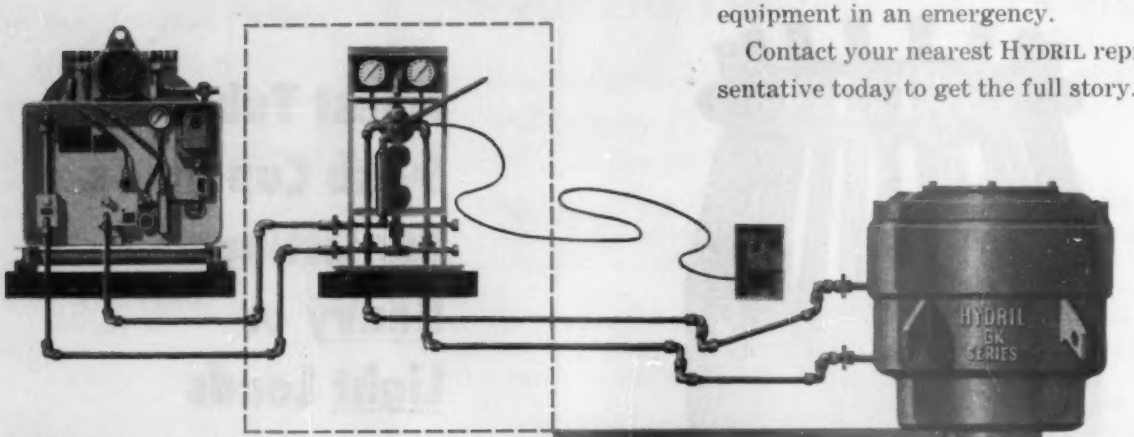
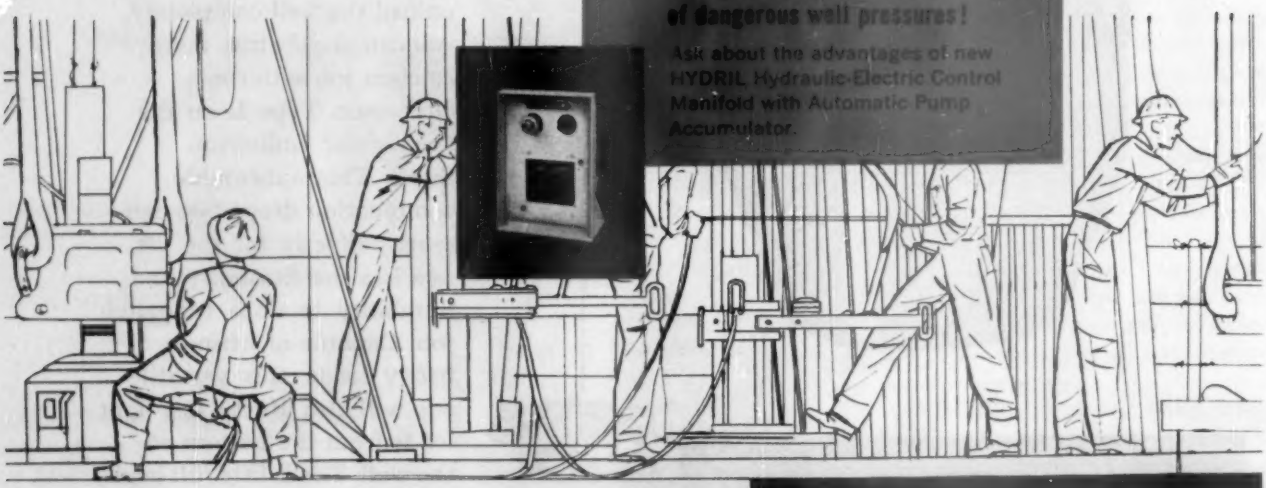


See pages 2555-8 of Composite Catalog, 21st Edition.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HYDRIL TAKES THE BLOW OUT OF BLOWOUTS

REPORT and INTERPRETATION

JOE B. ALFORD

EXECUTIVE SECRETARY
PETROLEUM BRANCH, AIME

Visit from Institute President

A long standing custom in AIME is for the Institute president to visit as many local sections and student chapters as possible during his term of office. Following this custom the Petroleum Branch was favored by a visit from our current president, H. DeWitt Smith, to several sections during the week of Nov. 7-11. His talks before meeting of the sections visited and informal conferences with members were highly beneficial to the Petroleum Branch members in acquiring a better understanding of AIME operation and organization.

The tour included visits with the Mid-Continent Local Section, the Kansas Local Section, the Hugoton and Panhandle Sections in a joint meeting, the Texas Technological College AIME Student Chapter, the South Plains Section, and an informal conference with some members of the Dallas Local Section. The writer accompanied President Smith throughout the trip. Robert B. Gilmore, Petroleum Branch chairman, and William D. Owsley, member of the Branch Executive Committee and chairman of the Branch Advertising Committee, made a portion of the tour.

Changing Membership Ratio

The talks made by President Smith before the sections visited were concerned with the possible future organization and operation of AIME. As shown in Table 1 the ratio of AIME membership in the three Branches is now undergoing a considerable change and will probably continue to do so in the next several years. (For example, the 1955 figures shown in Table 1 were on Jan. 1, and as of this writing the percentages are: Mining 43.34; Metals 24.54; Petroleum 31.71.) This changing ratio of membership indicates the need to study Institute organization for the benefit of all three Branches and their various professional divisions.

TABLE 1 — CHANGING RATIO OF AIME MEMBERSHIP

	By Percentage in Branches				
	1946	1950	1955	1960	1963
Mining	56	52	45	39	36
Metals	27	25	25	27	28
Petroleum	17	23	30	34	36

Accordingly, the Institute Board of Directors, in Feb., 1955, authorized the appointment of a Long Range Planning Committee. Subsequently President Smith appointed Andrew Fletcher, past president for the Mining Branch, Leo F. Reinartz, past president for the Metals Branch, and Carl E. Reistle, Jr., president-elect for the Petroleum Branch, as members of this Committee.

PANHANDLE SECTION OFFICERS—Back row, left to right: Donald E. Radtke, director and past chairman; William D. Owsley, member of Petroleum Branch Executive Committee; Don W. Jackson, secretary-treasurer. Front row: Henry J. Rose, chairman; AIME President Smith.

HUGOTON SECTION OFFICERS — Back row, left to right: Clifford R. Horn, section delegate; Claud P. Pyeatte, director; AIME President Smith. Front row: R. C. Dickson, secretary-treasurer; William H. Flood, Jr., director.

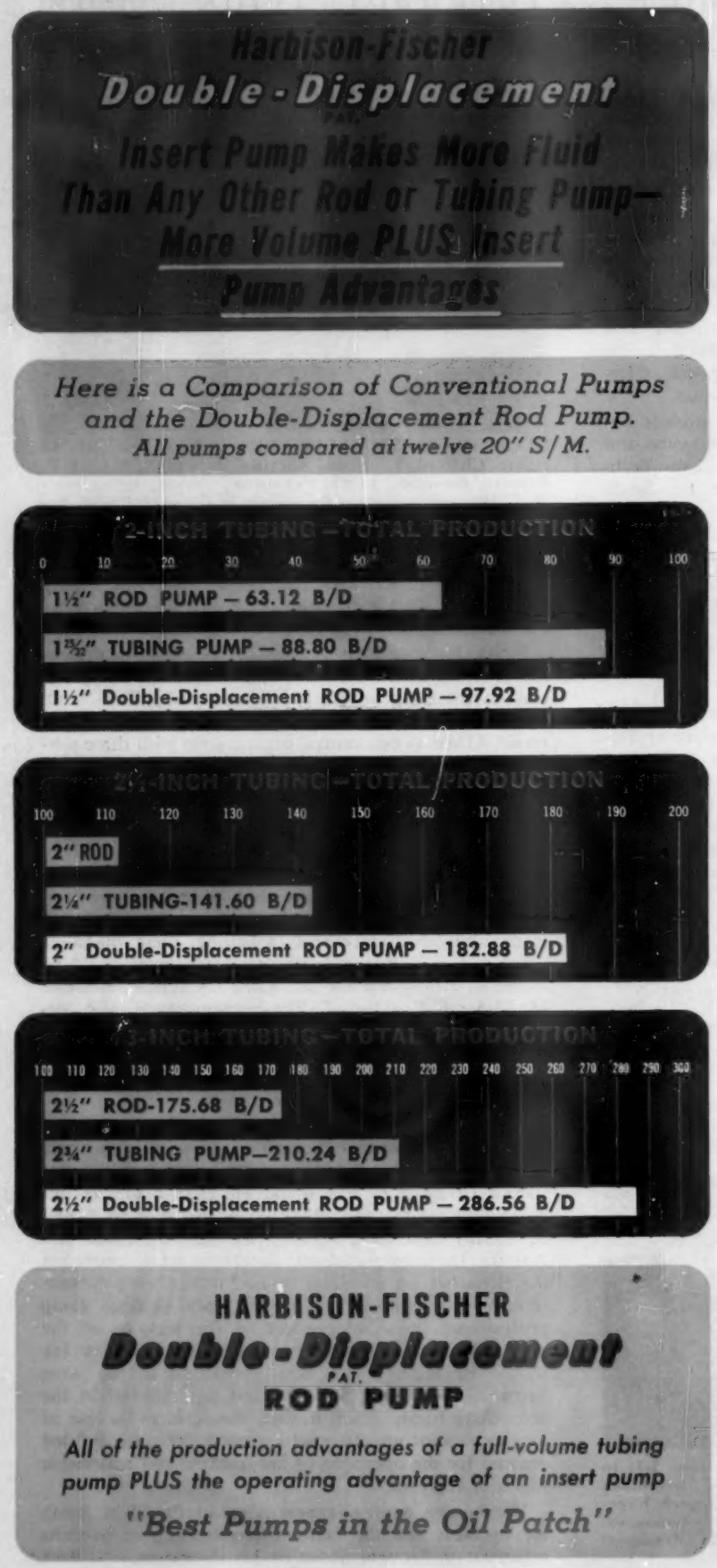
Smith reported that during the months since February the Committee has made good preliminary progress on the study of Institute organization. Two basic concepts of organization have been explored: (1) To retain AIME as one central organization with three subsidiary branches or organizational units; (2) To reorganize AIME as the American Institute of Mineral Engineers with three autonomous member institutes in the fields of Mining, Metals and Petroleum.

Opinions on Reorganization

Preliminary memoranda on these proposals have been circulated to various groups in the Institute and a good many individual members, soliciting their opinions. Smith reported that no enthusiasm whatever could be found in any group for the name "American Institute of Mineral Engineers." These memoranda also developed strong opinion in all three Branches that the AIME should be basically maintained as an over-all professional society for engineering in the mineral industries in the United States.

President Smith stated further that the Long Range Planning Committee will continue its study of Institute organization and will possibly employ an outside consultant to assist in this work. He then expressed his personal views that the AIME Board of Directors should be equally distributed between the three Branches and that the Institute presidency should be rotated between the Branches on an equal basis. Further, each Branch should be free to set up its own local sections along professional lines independent of the sections of the other Branches. Also, the Institute initiation fee should be reduced but dues should be at the same figure for all three Branches and not reduced in the immediate future. Each Branch should have the use of any surplus income after setting out a certain stipulated amount for the operation of the Institute and reasonable financial reserves.

We hereby express appreciation to President Smith for his visit and the better understanding of Institute organization brought about by his discussion. ★★★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Than Any Other Rod or Tubing Pump—
More Volume PLUS Insert
Pump Advantages
Here is a Comparison of Conventional Pumps
and the Double-Displacement Rod Pump.
All pumps compared at twelve 20" S/M.
2-INCH TUBING—TOTAL PRODUCTION
0 10 20 30 40 50 60 70 80 90 100
1½" ROD PUMP — 63.12 B/D
1 25/32" TUBING PUMP — 88.80 B/D
1½" Double-Displacement ROD PUMP — 97.92 B/D
2½-INCH TUBING—TOTAL PRODUCTION
100 110 120 130 140 150 160 170 180 190 200
2" ROD
2¼" TUBING-141.60 B/D
2" Double-Displacement ROD PUMP — 182.88 B/D
3-INCH TUBING—TOTAL PRODUCTION
100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
2½" ROD-175.68 B/D
2¾" TUBING PUMP—210.24 B/D
2½" Double-Displacement ROD PUMP — 286.56 B/D
HARBISON-FISCHER
Double-Displacement
PAT.
ROD PUMP
All of the production advantages of a full-volume tubing
pump PLUS the operating advantage of an insert pump
"Best Pumps in the Oil Patch"

Eighteen Paper Meet Planned at Texas A&M

Eighteen technical papers will be presented at a meeting to be held at A&M College of Texas on Jan. 9 and 10. Sponsors of the meeting will be the AIME Student Chapters of the University of Texas and A&M College of Texas. The meeting will be held at the A&M Memorial Student Center, College Station, Tex.

THE PROGRAM

Evaluation of Fluid Input Wells by Pressure Build-up Analysis, A. R. Groeneman, Sinclair Oil and Gas Co.; *Water and Gas Coning in Wells Completed in Homogeneous Sands*, K. E. Montague and M. D. Noble, Sun Oil Co.; *Studies of Pressure Distribution in Bounded Reservoirs at Steady-State*, C. S. Matthews and H. C. Lefkovits, Shell Development Co.; and *Comparison of Pressure Distribution During Depletion of Tilted and Horizontal Reservoirs*, D. S. Howard, Jr., and H. H. Rachford, Jr., Humble Oil and Refining Co.

A Reservoir Study of the Greater Clareton Area, Wyoming, Core Laboratories, Inc.; *Hydraulic Fracturing as Applied to the Chalk Rock, Caddo-Pine Island Field, Caddo Parish, Louisiana*, B. F. Patterson, The Texas Co.; *Sampling and Analysis Procedures for Oil Reservoir Fluids*, Frank O. Reudelhuber, Core Laboratories, Inc.; *Generalized Pressure Distribution and Gas Mass in Pipe Lines*, D. O. Atkinson and Paul B. Crawford, TPRC, A&M College; and *Secondary Recovery Potentialities of Buckrange Reservoir, Stevens Oil Field, Columbia, Nevada, and Ouachita Counties, Arkansas*, Paul Meadows and Murphy Hawkins, U.S. Bureau of Mines.

Determination of Fluid Saturation in Porous Media with a Radiocobalt Tracer and Application to Petroleum Production Research, Leonard B. Lipson and L. S. Gournay, University of Houston; *Radioactive Isotopes in Petroleum Production Research*, J. W. Watkins, H. N. Dunning, F. E. Armstrong, R. J. Heemnere, Lun Hsiao, U.S. Bureau of Mines; *Scale Limitations in Potentiometric Model Construction*, A. S. Odeh, H. B. Bradley, and J. P. Heller, Magnolia Petroleum Co.; *Bubble Formation in Petroleum Reservoirs*, Denton R. Wieland and Harvey T. Kennedy, A&M College of Texas; and *Interfacial Tension of Water and Methane with Minor Components*, E. F. Newman and E. W. Hough, University of Texas.

Cloud Point Determination of Crude Oils under Dymanic Conditions, James E. Howell and Frank Jessen, University of Texas; *The Significance of Mud Viscosity*, W. C. Goins, Gulf Oil Corp.; *A Lightweight, Low Water-Loss, Oil Emulsion Cement for Use in Oil Wells*, G. K. Dumbauld, F. A. Brooks, Jr., B. E. Morgan, and G. W. Binkley, Humble Oil & Refining Co.; *Dexet, a New Oil Well Cementing Material*, Dowell, Inc.

CORRECTION

Two errors were made in Technical Note 316, "Fluid Mapper Model Studies of Mobility Ratio," published on page 49 in the Nov., 1955, issue of JOURNAL OF PETROLEUM TECHNOLOGY. In the Introduction of the paper, the equations should have read:

". . . The mobility ratio, M, is defined as:

$$M = \frac{k/\mu \text{ (displaced fluid)}}{k/\mu \text{ (displacing fluid)}}$$

where k = effective permeability and μ = viscosity.

"When the displacing fluid is miscible with the displaced fluid, the permeabilities are equal and the mobility ratio may be expressed as a ratio of viscosities:

$$M = \frac{\mu \text{ (displacing fluid)}}{\mu \text{ (displaced fluid)}} \text{ "}$$

PERSONALS *of Petroleum Branch Members*

WILLIAM F. SHELTON has joined Creole Petroleum Corp. He graduated with a degree in petroleum engineering from the Colorado School of Mines. Shelton is a senior petroleum engineer with Creole in the San Joaquin District of the Eastern Div.

DUES BILLS IN MAIL

Pursuant to Article II, Section 2, of the by-laws of the AIME, notice is hereby given that dues for the year 1956 are payable Jan. 1, 1956, as follows: Members and Associate Members, $20; Junior Members for the first six years of Junior Membership, $12, and thereafter, $17; Student Associates (including an annual subscription to a monthly journal), $4.50.

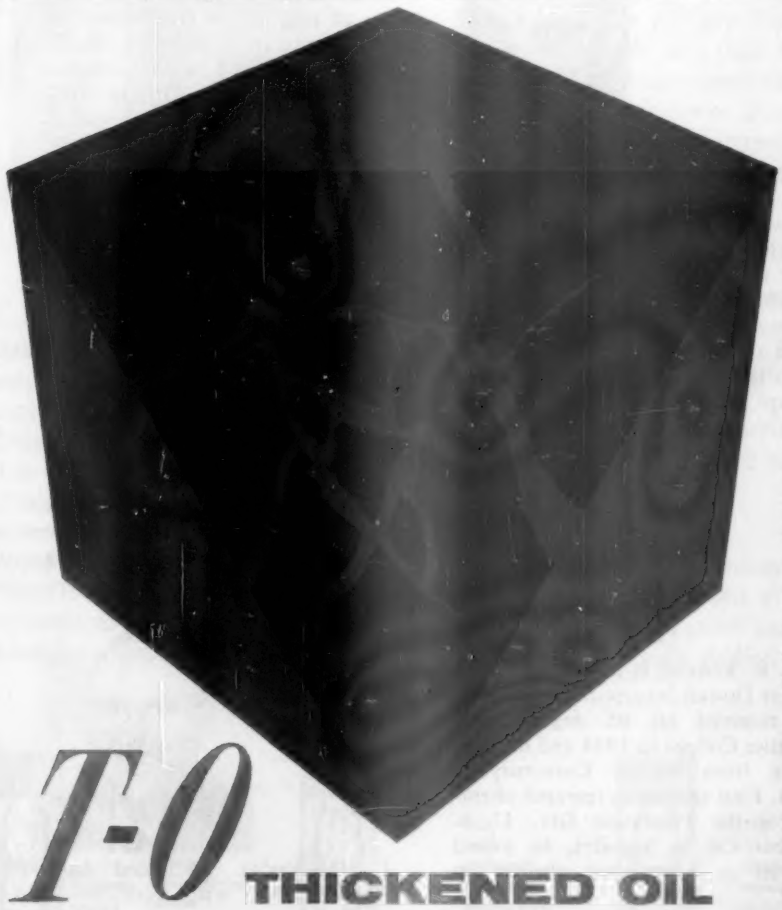
GABOR DESSAU is now at the Technion (Hebrew Institute of Technology) in Haifa, Israel. He will be there for one year as UNESCO advisor on the setting up of a geological engineering and mining department. After retiring in Sept., 1953, from Italian government service, he has continued as charge' de cours of mineral deposits at the University of Naples. From its inception, he has been in charge of the Uranium Prospecting Centre (Centro Ricerche Minerali Radioattivi) of the ENI-AGIP group.

☆

Dowell Incorporated has announced changes involving three AIME members. EARL J. DAVIS has been named assistant to the general manager and transferred to the Tulsa general offices of the company. He formerly was area manager in Dowell's Illinois District. JAMES R. PAUL, chairman of the AIME Kansas Local Section, has been transferred to Carmi, Ill., from Wichita, Kans., to fill the vacancy created by the promotion of Davis. S. R. WEST will replace Paul as district engineer in Kansas for Dowell. He was formerly located in Great Bend.

☆

RODNEY S. DURKEE, chairman of the board of Lane-Wells and a member of the executive committee of Dresser Industries, Inc., has been elected president of the California Manufacturers Association for the 1955-56 fiscal year. Lane-Wells has also announced changes in positions of other AIME members. JAMES D. HUGHES, formerly vice-president-sales, will now direct the sales and service activities of the company. JOHN C. STICK, JR., formerly the company's chief geophysical engineer, has been appointed chief engineer in the absence of V. L. FORSYTH, who is temporarily on special assignment as administrative assistant to the president. J. SHANNON BAKER has assumed the duties of the chief geophysical engineer. J. M. HENDERSON, Gulf Coast Div. Manager, has been promoted to manager sales and service for the company. R. E. BUSH has been advanced to manager of the Gulf Coast Div.



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HIGH VISCOSITY
for good sand carrying ability

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for deeper and better fractures

INTERNAL BREAKER
for faster, more complete clean-up

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for lower injection pressure

GOOD COMPATIBILITY
with demulsifying agents or additives such as Adomite to lower fluid loss.

Fracturing treatments with T-O are giving excellent results. A gas well in Hansford County, Texas, increased from a potential of 9,000 to 68,000 MCF after treatment with 20,000 gallons of T-O (made from kerosene). T-O approaches the ideal fracturing fluid. Your nearest Chemical Process Company office will be glad to give you additional information, or write to us at P. O. Box 831 in Breckenridge, Texas. There is no obligation.

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MEET the AUTHORS

A. R. HENDRICKSON was graduated from Beloit College, Wisconsin, in 1949 with a BS degree in organic chemistry. He did post graduate work at the University of New Hampshire, receiving his MS degree in 1950. He joined Dowell Incorporated, Tulsa, as a chemist shortly thereafter.

G. L. FOSTER holds a BS from Ottawa (Kansas) University and a MS degree from Kansas State College. He was employed by Dowell Incorporated as a chemist in 1952, and was promoted to his present position of laboratory group leader at Tulsa last year.

R. B. ROSENE is laboratory director for Dowell Incorporated at Tulsa. He received his BS degree from Whittier College in 1944 and his doctorate from Purdue University in 1951. First serving as research chemist for the Plantation Div., U. S. Rubber Co. in Sumatra, he joined Dowell as a research chemist in 1952.

A picture and biographical sketch of HENRY H. RACHFORD, JR., were published in the November, 1955, issue of JOURNAL OF PETROLEUM TECHNOLOGY.

W. P. SCHULTZ received a BS degree in chemical engineering from Rice Institute in 1947. Until 1955 he was employed by Humble Oil & Refining Co. He is now employed by Core Laboratories, Inc., and is a member of the Engineering and Consulting Dept. in Dallas.

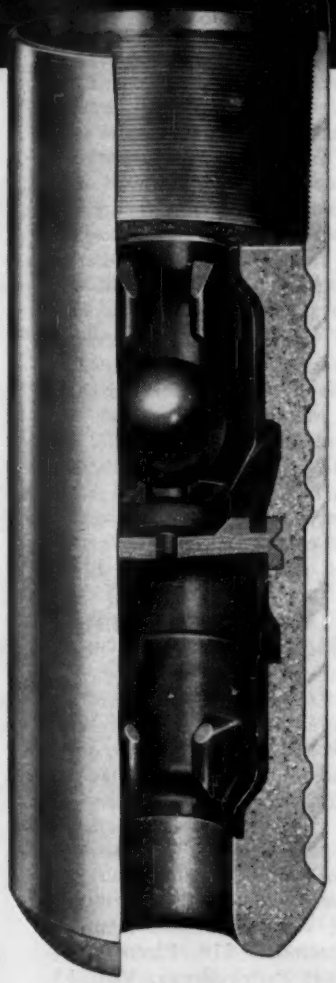
R. A. SEBAN is an associate professor of mechanical engineering at the University of California, Berkeley. He holds BS and PhD degrees received from the university in 1938 and 1948, respectively. His research and teaching experience primarily cerns heat transfer.

FRANK G. MILLER is professor and head of petroleum engineering at Stanford University. He holds MS and PhD degrees awarded by the University of California, specializing in oil-reservoir engineering.

L. C. VOGEL graduated from UCLA in 1949 with a degree in

AUTOMATIC, REGULATED FILL OF THE CASING AS IT IS BEING RUN

***PROTECTION AGAINST DESTRUCTIVE HIGH-PRESSURE SURGES**



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FILL-UP SHOES AND COLLARS

Baker Flexiflow Fill-Up Equipment, a new companion line to Baker Differential Fill-Up Equipment is designed to be run in wells of moderate depth.

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Baker Flexiflow Fill-Up Equipment contains a variable valve (Self-Adjusting Flow Control Diaphragm) that automatically opens wider or closes down to provide MINIMUM BOTTOM-HOLE PRESSURE INCREASES and regulated fill of the casing.

POSITIVE BALL-TYPE BACK-PRESSURE VALVE FOR CEMENTING

A Ball-Type, Back-Pressure Valve for floating or cementing can be brought into action at any time by applying a pressure of approximately 700 psi to the casing. See Figs. 2 and 3 below.

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The internal parts of Flexiflow Fill-Up Shoes and Collars consist of readily drillable concrete, a small amount of Bakelite and synthetic rubber.

ECONOMICAL

Baker Flexiflow Fill-Up Equipment not only permits the casing to be run more rapidly with greatly reduced pressure increases or surges on the formations below the shoe, but in addition, by eliminating the surface-filling operation, saves an additional amount of rig time. When these advantages are considered, Flexiflow Equipment is much more economical to run than conventional floating equipment.

***Pressure surges over 5,000 psi can be created each time a joint of casing equipped with conventional floating equipment is lowered under certain slim hole clearances.**

High-Pressure surges can fracture and weaken a formation sufficiently to cause lost circulation or the failure of a primary cement job.

These destructive, high-pressure surges can be reduced . . .

- **by increasing the lowering time per joint**
- **by increasing the casing clearance**

or

- **by running Baker Flexiflow (or Differential) Fill-Up Shoes and Collars**

NOTE:

Baker Fill-Up Equipment contains a variable valve that automatically opens up and adjusts to maintain minimum bottom-hole pressure as the casing is being run.

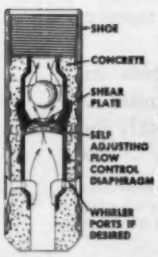

FIG. 1 Casing Filling while going in the hole

FIG. 2 Ball pumped through diaphragm

FIG. 3 Ball shut-off against cement back-pressure

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POLICIES FOR 1956 AIME PUBLICATIONS ESTABLISHED

Pursuant to Article X of the by-laws of the AIME, the following information is hereby given as to the "conditions, prices, and terms under which the various classes of members, and Student Associates, severally, shall be privileged to obtain publications of the Institute during the ensuing year."

Publications authorized for issue in 1956 include the following: *Mining Engineering*, published monthly, containing material, including technical papers, of interest to those engaged in exploration, mining geology and geophysics; metal, nonmetallic, and coal mining and beneficiation; and fuel technology. The *Journal of Metals*, published monthly, containing material, including technical papers, of interest to those engaged in nonferrous smelting and refining, iron and steel production, and physical metallurgy. The JOURNAL OF PETROLEUM TECHNOLOGY, published monthly in Dallas, containing material, including technical papers, of interest to those engaged in petroleum and natural gas drilling and production.

Annual subscriptions to any one of the above journals will be provided all members in good standing without further charge, a subscription credit of $6 for members and $4 for Students Associates being included in the dues paid. (A member ceases to be in good standing if current dues are not paid by April 1). If more than one of the monthly journals is requested, $4 extra will be charged for an annual subscription, or 75c for single copies of regular issues and $1.50 for special issues. The nonmember subscription price for each journal is $8 in the Americas and U.S. possessions; foreign, $10; for single issues 75c in the Americas; $1.00 foreign for regular issues; $1.50 for special issues. Student Associates will be entitled to the same privileges for all publications as members. AIME members subscribing to more than one of each of the three monthly journals will be billed at the nonmember rate of $8 per year, domestic; $10 foreign, for the extra subscription(s).

Three volumes of *"Transactions"* are authorized for 1956 publication, as follows: No. 202, Mining Branch; No. 203, Metals Branch; and No. 204, Petroleum Branch. *Volumes 202 and 204 will be available to members at $3.50 each for a first copy if paid for in advance with dues;* otherwise at the nonmember rate of $7 less 30 per cent. Nonmembers $7 in the United States; Foreign $7.50. Volume 203 will be available to members at $4.50 each for a first copy if paid for in advance with dues; otherwise at the nonmember rate of $9 less 30 per cent. Nonmembers $9 in the United States, foreign $9.75.

Special volumes now planned for publication in 1956 include the following: *Open Hearth Proceedings*, Vol. 39, price to AIME members $7; nonmembers, $10. *Blast Furnace, Coke Oven, and Raw Materials Proceedings*, Vol. 15, AIME members $7; nonmembers $10. *Electric Furnace Steel Proceedings*, Vol. 13, AIME members $7; nonmembers $10. *Statistics of Oil and Gas Development and Production*, Vol. 9, covering data for the year 1954, members $5, nonmembers $10. Proceedings of Nigara Falls Conference on Reactive Metals tentative; price to be determined.

If dues are paid subsequent to January 31, back issues of Institute publications will be supplied only if adequate stocks are on hand. A member is not entitled to receive a volume of *"Transactions,"* or a special volume, in lieu of a monthly journal, free of charge on membership. Members in arrears for dues are not entitled to special members' prices for publications.

Rocky Mountain Members may have their choice of an annual subscription to one of the monthly journals on request. ★★★

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For further details see page 32

EMPLOYMENT NOTICES

The JOURNAL OF PETROLEUM TECHNOLOGY will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1. These replies will be forwarded unopened and no fees are involved. Replies for notice listed by code W2555(a) are to be sent to: Engineering Societies Personnel Service, 8 West 40th St., Room 1207, New York 18, N. Y. The ESPS collects a fee from applicants actually placed.

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☆ Combination Petroleum-Geological Engineer or Petroleum Engineer competent in geology, with one to two years' experience; Gulf Coast experience preferred. Reserves and evaluation work for expanding gas transmission company located in Houston. Reply stating experience, desired salary and approximate availability date. Code 594.

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Petroleum Engineer between 28 and 35 years of age with field experience and interest in reserves and valuation work. New York financial institution offers opportunity for experience and advancement. Please send resume of personal history, experience, and recent photograph. Replies will be considered strictly confidential. Write P. O. Box 226, Church Street Station, New York 8, N. Y., Dept. 12.

☆ Petroleum Engineer, four or five years' experience with emphasis on valuation and reservoir engineering. Must be free to travel with Dallas as headquarters. Initial letter application should set out past experience in detail, education and salary requirements. Code 595.

☆ Professor of Petroleum Engineering to be responsible for undergraduate curriculum and graduate courses. MS or PhD. Interest in research desired and full cooperation of university assured. Rank and salary dependent upon education and experience. Code 596.

☆ Assistant or Associate Professor of Mining Engineering to teach courses in mining and petroleum engineering.

(Continued on Page 37)

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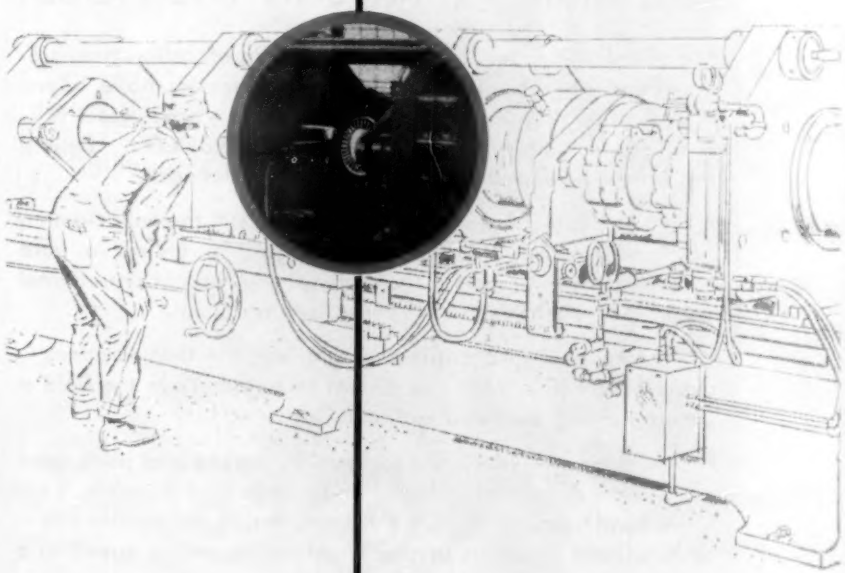

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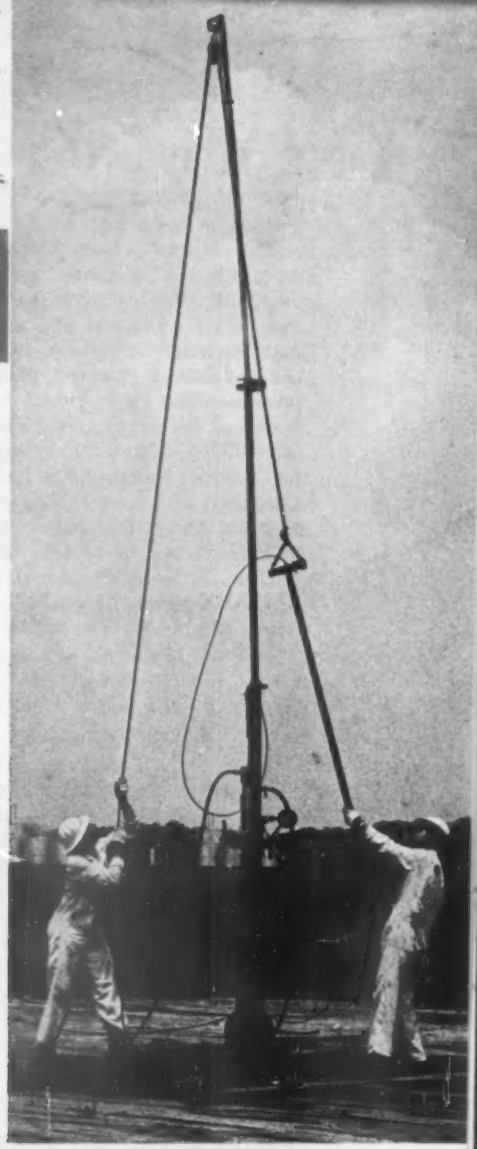

PGAC-558

(Above) PGAC service crew preparing to lower new 1-11/16" Simultaneous Radiation Logging instrument through 2" tubing.

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- **Moreover, PGAC *originated* and was the first company—*years before any other*—to deliver immediately in the field a simultaneously recorded radiation log.**
- Furthermore, PGAC has successfully logged and perforated the world's deepest (17,570 ft.) and hottest (349°F.) wells. Such know-how leads to PGAC's constantly improved instruments—tools without equal in accuracy, safety, operating speed and efficiency.

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President-Elect Reistle Speaks at Arizona Meet

AIME President-Elect Carl E. Reistle, Jr., was the featured speaker before some 700 dinner guests attending the annual Arizona Section meeting in Tucson, Ariz., on Dec. 5. The Humble Oil and Refining Co. vice-president spoke on "Offshore Developments in the Oil Industry."

Reistle also spoke on the morning of Dec. 5 to the AIME Student Chapter at the University of Arizona, telling the students what management looks for when hiring engineers. During both the morning and evening talks, President-Elect Reistle briefly outlined recent developments in AIME affairs.

Other guests representing the Petroleum Branch at the annual Arizona Section meeting were Branch Chairman Robert B. Gilmore, DeGolyer and MacNaughton; Joe B. Alford, executive secretary; and R. W. Taylor, editor of JOURNAL OF PETROLEUM TECHNOLOGY.

U S C Chapter Activities

The University of Southern California Student Chapter of AIME recently took a field trip to the Union Oil Co. water flood at Dominguez Oil field. Several other field trips are planned for this chapter with 24 active members.

The chapter holds monthly meetings, featuring speakers from industry. The highlight of the year will be the annual Spring Meeting on the USC campus, for the students and men from industry.

Officers for the 1955-56 school year are: Leland Cecil, president; Allen Nelson, vice-president; Bruce Melkonian, corresponding secretary; George Heckler, recording secretary; and R. L. Perrine, California Research Corp., counselor.

Student Chapter Reorganized

The Missouri School of Mines AIME Student Chapter has been reorganized and now consists of three active sections, Mining, Petroleum, and Metallurgy. Each section has its own slate of officers and own programs. Joint meetings of the sections featuring discussions of subjects of mutual interest are also held. Until this reorganization the petroleum students had their own petroleum club, with mining students dominating the AIME Student Chapter.

Petroleum Section officers are: J. W. Ware, chairman; B. Malson, vice-chairman; J. Lutz, secretary; and Henry Lamb, treasurer. Prof. J. Paul Roston is faculty section advisor.

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PETROLEUM PROGRAM BEING DEVELOPED for AIME ANNUAL MEETING

Six papers have been definitely scheduled for presentation at Petroleum technical sessions at the AIME Annual Meeting in New York. Additional papers are to be added to the program, which will be held at the Statler Hotel during the course of the Annual Meeting, Feb. 19-23.

Petroleum Papers

Names of papers and authors scheduled are:

Problems Related to Negotiation of Foreign Oil Concessions, by Burney Brady, Continental Oil Co.

Gilsonite and Its Relation to Oil, by Park L. Morse or R. E. Nelson, American Gilsonite Co.

The Importance of Foreign Oil to Our Military Services, by Admiral E. E. Elber (USN, retired), Director of Engineering for Bucknell University.

Foreign Service and Equipment, by A. W. McKinney, president of National Supply Co.

The Future Growth and Financial Requirements of the World Petroleum Industry, by Joseph E. Pogue, consultant for Chase Manhattan Bank.

Long Range Supply and Demand, by Charles Hedlund, manager of Coordination and Economics Dept., Standard Oil Co. (N. J.).

The program will probably consist of 10 papers when completed. Selected speakers are being requested to present papers on the subjects of: application of electric computing to the oil industry, the habitat of oil, the economics of well spacing, and sonic drilling.

Host Section

Development of the technical program for this meeting and arrangements for the speaker at the Petroleum Branch Dinner are being handled by the New York Petroleum Section. Zeb Mayhew, Standard Oil Co. (N.J.) is program chairman, replacing Henry E. McAuliffe, Socony-Mobil, who was recently transferred to Colombia. Dale Nix, Arabian American, is chairman of the New York Petroleum Section.

This is the first year in which the New York Petroleum Section has had charge of the Petroleum activities for the Annual Meeting. The formation of the New York Petroleum Section in 1954 made it possible and desirable for this section to develop the program. Prior to this time the Petroleum Branch Technology Committee has handled all Annual Meeting programs.

The Petroleum Branch Executive Committee is pleased with the program which is being developed. Papers selected to be presented on this program are of particular interest to people of the New York area; therefore, a larger attendance than in past years is expected. When held in New York on alternate years, this meeting will serve as somewhat of a regional meeting for the New York area, and as such it can be of great value to the New York Petroleum Section.

Tentative Petroleum Program

Saturday, Feb. 18
10:00 a.m.—Meeting of Council of Section Delegates

Sunday, Feb. 19
2:00 p.m.—Open Meeting of AIME Board of Directors

Monday, Feb. 20
9:00 a.m.—Open Meeting of Petroleum Branch Executive Committee
Noon—AIME Welcoming Luncheon
Afternoon—Petroleum Technical Session

Tuesday, Feb. 21
Morning—Petroleum Technical Session
Afternoon—Annual Production Review Session
Evening—Petroleum Branch Dinner

Wednesday, Feb. 22
Morning—Petroleum Technical Session
Evening—AIME Annual Banquet and Dance

Bob Cannon (left), vice-president of the University of Oklahoma of Pi Epsilon Tau, presents a bronze key plaque to William D. Owsley, vice-president of Halliburton Oil Well Cementing Co. and a member of the Petroleum Branch Executive Committee. Through presentation of this plaque, Owsley was made an honorary member of the national honorary petroleum engineer's fraternity. At this meeting he delivered a talk entitled "The Petroleum Engineer — His Way of Life."

New AIME Director Named

At the recent AIME Board meeting, Charles R. Kuzell was named to succeed E. L. Oliver, deceased, for the latter's unexpired term as AIME Director, until February, 1956. Kuzell's regular term as director for three years begins at that time.

HAVE YOU CHANGED YOUR ADDRESS?

In order that publications and correspondence may reach you promptly, the Petroleum Branch, AIME, should be advised as soon as possible of any change in your address, *preferably a month before the change becomes effective.* For the AIME directory and for the Personals column of the JOURNAL OF PETROLEUM TECHNOLOGY, additional information is desired. The form below is provided for your convenience, and should be sent to Petroleum Branch, AIME, 800 Fidelity Union Bldg., Dallas 1, Tex.

Name_____

Membership No._____

Old Address_____

_____

New Address for Publications_____

_____

_____

Address for Directory Listing and Job Title_____

_____

List below your former title or company position, nature of your new position, or other information of interest to your associates for publication in the JOURNAL OF PETROLEUM TECHNOLOGY.

_____

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One month normally required for change of address.

In New Member Applications

BRANCH SHOWS 43 PER CENT RISE

VIRGINIA B. DAGGETT | ASSISTANT SECRETARY PETROLEUM BRANCH, AIME

November was another record-breaking month for membership, with 193 applications received. The previous high for a single month set in October was 186. As we entered the last month in the 1955 membership contest, 1,111 applications had been received, up 43.4 per cent from 775 at the same point last year.

The outstanding increase of the Gulf Coast Local Section continued, boosted by membership committee activity at its two-day Formation Evaluation Symposium in late October. Ninety-nine applications were credited to Gulf Coast in November, giving the section a 34.7 per cent increase for the year to date. It is interesting to note that the largest Petroleum Branch section now has the second highest per cent increase, exceeded only by two percentage points by the Panhandle Section. Contest standings for all sections are shown elsewhere on this page.

All applications postmarked by midnight, December 31, will be eligible to count in this year's membership contest. The winning section in each of the four groups will be awarded a slide projector, an AIME banner, or other suitable prize.

PETROLEUM BRANCH MEMBERSHIP CONTEST

Eleven-Months Report

Covering Applications Received Jan. 1-Nov. 30, 1955

Section	Jan. 1 Membership	Applications Received	Per Cent Increase
Group A			
1. PANHANDLE	60	22	36.7
2. Hobbs	88	30	34.1
3. Mississippi	59	12	20.3
4. Billings Petroleum	61	12	19.7
5. Hugoton	27	5	18.5
6. North Texas	84	15	17.9
7. South Plains	51	1	2.0
Group B			
1. KANSAS	141	29	20.6
2. Denver Petroleum	141	28	19.9
East Texas	141	28	19.9
3. Lou-Ark	148	24	16.2
4. West Central Texas	135	12	8.9
5. Wyoming	152	13	8.6
6. Illinois Basin Petroleum	154	9	5.8
Group C			
1. DELTA	308	56	18.2
2. Venezuela Petroleum	194	32	16.5
3. Fort Worth	181	26	14.4
4. Oklahoma City	269	38	14.1
5. Permian Basin	352	41	11.6
6. New York Petroleum	212	19	9.0
7. San Joaquin Valley	169	13	7.7
Group D			
1. GULF COAST	929	322	34.7
2. Mid-Continent	553	76	13.7
3. Dallas	433	56	13.0
4. Southwest Texas	461	57	12.4
5. Southern California Petroleum	597	44	7.4
Total Applications from Sections		1020	
Miscellaneous		44	
Foreign		47	
Total Applications Received Jan. 1-Nov.30		1111	

Proposed for Membership, Petroleum Branch, AIME

California
Bell—Marquis, Duane Elvin (M).
Huntington Park—Subt, Frederick George (A).
La Habra—Hildebrand, Alexander (M).
Los Angeles—Marshall, Ira Allison, Jr. (M); Stanley, Charles Calvin (A); Travers, William J. (R, M).
Taft—Murphy, Denis Michael (J).
Ventura—Larson, Robert Reynold (C/S-J-M).
Colorado
Denver—Gordon, Archie (M); Sneed, Robert W. (C/S-J-M).
Illinois
Mt. Vernon—Dost, Raymond Matthew (M).
Kansas
El Dorado—Halstead, Louis Norman (M).
Wichita—Gary, John Thomas (C/S-J-M); Steves, Herbert Burdett (M).
Louisiana
Baton Rouge—Graves, Ernest Doyle, Jr. (J).
Franklin—Baribault, Jules Donat (M).
Lafayette—Baker, Joe B., Jr. (A); Haube, Edmund Dale (M); Thomas, Earl F. (M).
New Iberia—Young, Ola Olympia (A).
New Orleans—Favier, Pierre Pascal (M); Keating, Charles Crews (J); Norman, Benjamin Franklin, Jr. (M).
Shreveport—Bynum, Winfred Wilson (M); Haynes, James Edward (M); Martin, Monty G. (M); Thompson, Robert Earl (J); Wood, Jesse Winston (M).
Venice—Dawsey, Albert Louis, Jr. (J); Suggs, William Pat (J).
Michigan
Grand Rapids—Lazar, Albert (M).
New Mexico
Hobbs—Dennis, Jack Milton (J); Frick, Kenneth Dare (M); Lucchi, Harold Joseph (J); Palmer, Aubrey King, Jr. (R, C/S-S-J).
New York
Bedford Village—Davis, Dwight Ed (R, M).
New York—Black, Thomas Oscar, Jr. (J); Volkman, William Edward (M); Wright, Albert (M).
Pound Ridge—Coenen, Edward Joseph (M).
Oklahoma
Ardmore—Hill, John James (M).
Drumright—Frazier, Ernest Richard (A).
Lindsay—Fisher, Charles Albert (J).
Oklahoma City—Lightner, Earl Miller (R, C/S-S-M).
Purcell—Michie, Troy Willard (J).
Tulsa—Bridwell, Harold Cloyd (J); Gardner, Dan Lewis (R, J); Hunt, Elton B., Jr. (C/S-J-M); Moody, Wayne Charles (M); Newcombe, Jack (M); Snow, Robert Dale (M); Stoore, Philip, Jr. (A); Tillerson, Roy Bernard (M).
Pennsylvania
Bradford—Wood, Quentin Eugene (M).
Texas
Abilene—Brogdon, Bill R. (M); Townley, Owen (M).
Amarillo—Tomlinson, Guy H., Jr. (M).
Bay City—Kilpatrick, Robert Emmett (M).
Baytown—Capshaw, Thomas David (J); Spriggs, Robert Paul (J).
Beaumont—Bateman, Sammie J. (M); Eckles, Wesley Webster (J); Hayes, Edwin Garwood (M); Maddux, Henry Sherman, Jr. (J); Noone, Edward James (M); Pruett, Gayle Moreland (M).
Beeville—Giese, Lester Edgar, Jr. (J); Withers, Bruce, Jr. (J).
Bellaire—Dawson, Arch (R, M); Dieckman, John June (J); Fuqua, Marjorie (M); Gore, George Houston (J); Hottman, Clarence Edward (J); McCurtain, Edmund Elum (J); Simmons, Franklin Page (J); Smaistria, Robert N. (J); Stelzer, Roland Brunn (J); Townley, John Paul (J).
Boling—Faden, James Root (J).
Dallas—Clote, Paul J. (J); Melsheimer, Albert Henry (R, M); Reeves, John Lloyd (J); Shaw, Roland Clark (A); Sinex, James Mitchell (M); Slusser, Marion Liles (M); Tompson, Gilbert Carr (C/S-J-M).
Fort Worth—Britton, Stanley Grant (M); Powers, Richard Earl (M); Robertson, John James (A); White, James Robert (M); Yager, Charles Ervin (M).
Galena Park—Ramey, Darol Keith (J); Shannon, William L. (M).
Genoa—Davies, William James (R, C/S-S-J).
Houston—Akkerman, William Herman (M); Ballard, Junius Chambers, Jr. (J); Banks, Overton Barnes (M); Barrett, Joe Bill (J); Beard, James Ijams (J); Blumberg, Randolph (J); Boyd, Walter Andrew, Jr. (J); Brixey, Austin Day, Jr. (M); Broussard, Douglas Eugene (M); Chisholm, James P. (J); Cobb, Lewis Allen (J); Colby, John Byron (A); Connelly, Francis Becker (J); Craig, Harry J., Jr. (J); Cralle, George Leroy (A); Crain, Marvin G. (J); Derrick, A. M., Jr. (C/S-J-M); Dewan, John Tierney (M); Diener, Milton Lawrence (M); Doyle, James Joe (M); Drummond, William Temple (J); Ekey, John Walter (J); Evans, John Billy (R, M); French, William Lee (J); Gimblet, Ernest Carlyle (M); Glasgow, Herschel Miller (J); Grimes, Erwin Elwood (J); Grissett, John Neal (J); Haddox, R. Putnam (C/S-J-M); Heiny, Rems Chandler (J); Henderson, Paul William (J); Hinerman, David Arthur (J); Hodgson, Glen Reid (M); Humble, James M. (J); Kellough, John Stevens (M); Koch, William Martin (M); La Croix, Sam Henry (J); Lawrence, William Jackson (M); Malek-Aslani, Morad (M); Manson, Donald Humphrey (M); Marshall, Ray W. (A); Martin, Richard Wendell (J); McKeever, Ira Everett, Jr. (J); Murphy, Arthur Gilman (J); Nelson, Paul Morwood (J); Nelson, William Paul (M); Oliver, Raymond Alexander (J); Phillips, William Lawrence (A); Pianta, James Eugene (J); Raabe, William Louis (J); Rehm, William Arthur (J); Reiter, William Arthur, Jr. (M); Rhodes, Roy Marvin (J); Riep, Otto (M); Robb, D. Douglas, Jr. (M); Robertson, Wayne W. (J); Starr, George James (M); Stovall, George Alston (J); Thomas, Bill Eugene (J); Thomas, Sherwood Lindsay (J); Trimble, Richard L. (M); Trowbridge, Charles Eugene (J); Vercellino, Wilton Canova (M); Vestermark, Lyle Armand (M); Wherry, R. Britton (J).
Katy—Burley, James D. (J); Corbell, Billy Joe (J); Gorden, Cecil Dennis (M); Hilton, Byron Lee (J); Thomas A. D. (M).
Liberty—Daniels, Whitfield Floyd (M).
Midland—Davis, Donald William (J); Fitzgerald, Thomas Allen (J); Fitzgerald, William Patton (J); Holley, Joseph Wilson (M); Jones, Samuel Clayton (M); Rockwood, Spencer Henry (R, M); Vickery, Jack Hill (M); Whitfield, Marion Anderson (A); Woodward, Maurice E. (M); Yarbrough, Richard William (J).
Monroe City—Baugh, Edgar Gratton (J); McCune, John Stanley (M); Pipes, Kenneth Paul (J).
Odessa—Langford, Billy J. (J).
Pampa—Michael, Dan Gauntt (J); Winter, Irwin Thomas (J).
San Antonio—Mitchell, John K. (A).
Thompsons—Grinstead, Fred Edward (J).
Tomball—Peterson, Gerald Lee (J).
Tyler—Williams, James Douglas (M).
Wharton—Eastman, Frank Allan (M); McCulloch, Robert Andrew (M).
White Oak—Haynie, Moss (A).
Wichita Falls—Graf, Arthur F. (C/S-J-M); Martin, Joseph Frederick (A); O'Neal, J. A. (A).
Winnsboro—Wofford, Chancey Jackson (J).
British West Indies
Trinidad—Howe, Stanley (J).
Canada
Calgary—Buckles, Robert Sheldon (J).
Regina—Foster, George Michael Henderson (M).
England
Birmingham—Cooper, Alan Charles (J).
Germany
Hamburg—Hehlert, Otto Ernst (M).
Persian Gulf
Qatar—O'Connell, Patrick D. A. (M).
Venezuela
Anaco—Bates, William Clifford (J).
Barcelona—Rhoads, Daniel Wayne (M).
Caracas—Cobb, Dow C. (A).

MEET THE AUTHORS

(Continued from Page 26)

chemistry. Following graduation he worked as research chemist on well completion for Oilwell Research, Inc. Joining Union Oil Co. in 1951, he is engaged in well completion work with the production research group of the Research Dept.

R. F. KRUEGER holds a BS degree in physics from Ripon College, Wisconsin, and a MA from the University of Illinois. Since 1948 he has worked for Union Oil Co. on secondary recovery and well completion problems and is section leader of the Well Completion and Field Service Group.

R. L. NEWACHECK is a senior mechanical engineer with Tracerlab, Inc., Western Div., joining the firm in 1950. He holds a BS degree in mechanical engineering from Kansas State College. After graduation he joined the Pacific Gas & Electric Co., and is a former instructor in blueprint reading.

E. E. ANDERSON received a BS degree in chemistry from San Diego State College in 1950. He joined Tracerlab, Inc., Western Div., as a radiochemist following work with Consolidated Aircraft Corp. He is presently carrying out development of a number of commercial radioisotope preparations and industrial applications.

JEROME KOHL was graduated from California Institute of Technology in 1940 with a major in applied chemistry. Prior to joining Tracerlab, Inc., in 1948, he was employed by Tide Water Associated Oil Co. He is now chief engineer for Tracelab's Western Div.

MOHAMED MORTADA received a BS degree in chemical engineering from the University of Cairo in 1946 and MS and PhD degrees in petroleum engineering from the University of California, Berkeley. Joining Magnolia Petroleum Co. in 1954, he is a senior research engineer for Magnolia's Production Div.

J. W. MCGHEE is employed in the secondary recovery section of the Cities Service Research and Development Co. He joined Cities Service after graduating from Oklahoma A&M College with a BS degree in chemistry in 1951.

JACK NEWCOMBE joined the Cities Service Research and Development Co. in 1947 after graduation from Oklahoma A&M College with an MS degree in chemistry. After four years' in petrochemicals and related work, he transferred to secondary recovery research in 1951.

M. J. RZASA joined the Cities Service Research and Development Co. in 1953 as manager of production and exploration research. Prior to that time he was employed by Stanolind Oil & Gas Co. He received his PhD in chemical engineering from the University of Michigan in 1947.

J. L. MARTIN is a supervising engineer in charge of well logging research at Atlantic Refining Co.'s Research and Development Laboratory in Dallas. He received BS and MS degrees in electrical engineering from Georgia Institute of Technology. He has been with Atlantic since his graduation in 1947.

(Continued to Page 37)

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WICHITA, KANSAS

NECROLOGY

Elected	Name	Date of Death
1915	George A. Macready	Nov. 10, 1955

EMPLOYMENT NOTICES

(Continued from Page 29)

MS degree or practical experience in field is desirable, preferably including work in petroleum engineering. Opportunity for direction of graduate courses, research and consulting. Applicant should be keenly interested in teaching and capable of developing new courses as needs arise. Rank and salary dependent on qualifications. Starting date, Feb. 1 or Sept. 1, 1956. Reply to: Prof. Philip C. Rosenthal, Chairman, Dept. of Mining & Metallurgy, 1509 University Ave., Madison 6, Wis.

Application Engineers, sales, mechanical, chemical or petroleum engineering or sales engineering fields. Will adapt reciprocating engines and compressors, centrifugal compressors, gas turbines and recommend design changes to meet needs of customers. Salary, $5400-$7200 a year. Location upstate New York. Code W2555(a).

PERSONNEL AVAILABLE

☆ Petroleum Engineer, 34, BS degree O.U., dependable. Experience: four years' practical drilling and production, three years' field engineering including completions, workover, GOR's and commission work. Employed, desires to relocate with independent or small organization in North Texas area. Code 269.

☆ Graduate Petroleum Engineer with six years' experience in drilling and production practices including workovers, well completions, and equipment. Currently employed with major company. Single, 32, and bilingual, desires responsible position with opportunity of advancement inside or outside U.S. Code 270.

☆ Graduate Petroleum Engineer seeks position as executive assistant or operations adviser with aggressive integrated company or independent in U.S. Twelve years' widely varied drilling and production experience with major in Venezuela. Good working knowledge of pipeline operations, reservoir engineering, gas repressuring plants, budgets and accounting. Last position was assistant superintendent drilling and production. Code 271.

Meet the Authors

(Continued from Page 35)

W. M. CAMPBELL received a BS in physics from Muskingum College in 1949 and an MS in physics from Ohio State University in 1951. He joined Atlantic Refining Co. after graduating and has worked mainly with well logging problems. He presently is an associate physicist in the company's Research and Development Dept.

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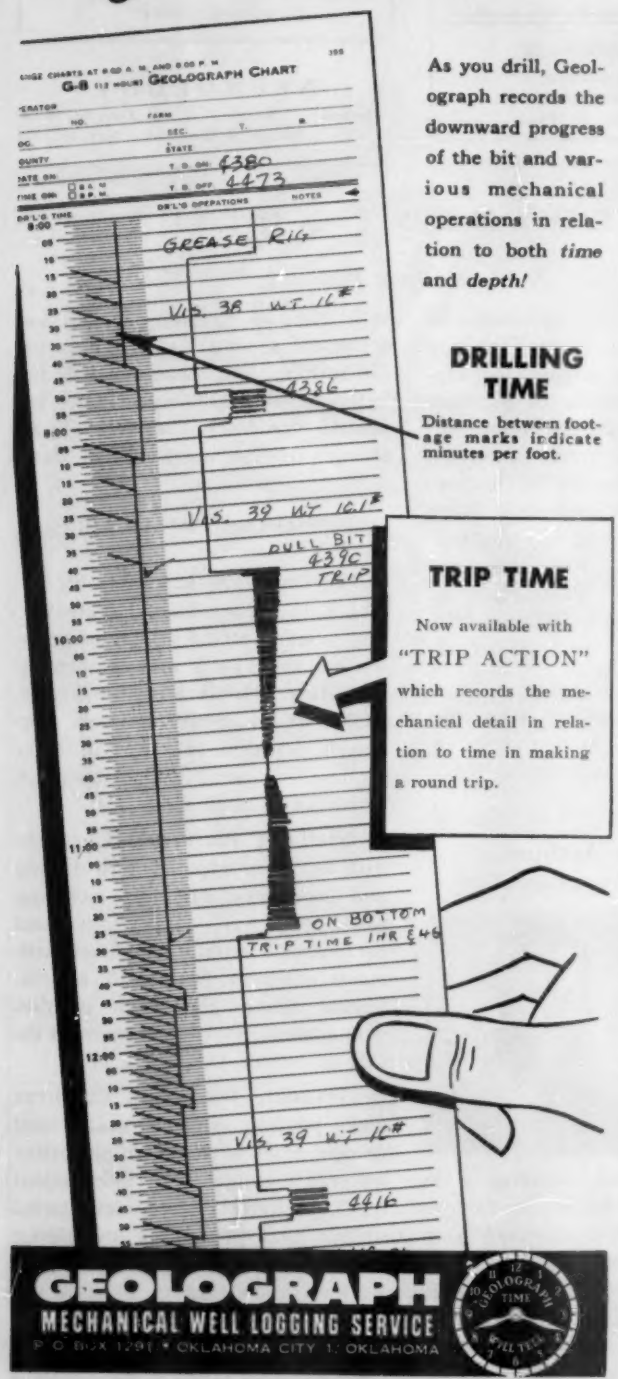

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NOMINATING COMMITTEE for 1957 AIME OFFICERS NAMED

The following have been named by the Council of Section Delegates, the Branch Councils, and the President of the Institute to constitute the Nominating Committee for AIME Officers in 1957. The committee will meet during the Annual Meeting of the Institute in Chicago, Feb. 20 to 23, 1956 and select the official slate. If the principal finds it impossible to attend, the alternate will act in his place; otherwise, the alternate will not be present at the meeting of the Committee. The names of the alternates are given in parentheses.

Appointment of President, with approval of Board of Directors: John S. Bell, Chairman, Humble Oil & Refining Co., 612 S. Flower St., Los Angeles, Calif. (Frank A. Ayer, 21 E. 40th St., New York, N. Y.); Hugo E. Johnson, Lake Superior Iron Ore Assn., 1400 Hanna Bldg., Cleveland, Ohio (John J. Golden, U. S. Steel Corp., 525 Wm. Penn Place, Pittsburgh); John Lokken, Dow Chemical Co., Box 351, Pittsburg, Calif. (W. W. Everett, Glen Alden Coal Co., 16 S. River St., Wilkes-Barre, Pa.)

Mining Branch Council: J. K. Richardson, Kennecott Copper Corp., Hurley, N. M.; M. D. Cooper, National Coal Assn., 5430 Aylesboro Ave., Pittsburgh 17, Pa.

Metals Branch Council: Frank T. Sisco, Engineering Foundation, 29 W. 39th St., New York, N. Y.

Executive Committee, Council of Section Delegates: Clark Wilson, New Park Mining Co., 904 Walker Bank Bldg., Salt Lake City, Utah.

Petroleum Branch Council: John R. McMillan, Monterey Oil Co., 430 Statler Bldg., Los Angeles, Calif. (Claude R. Hocott, Humble Oil & Ref. Co., 1200 Main St., Houston, Texas).

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District 3: S. S. Clarke, 429 Cherokee Ave., Baxter Springs, Kan.

District 4: Theron Reed, Owens-Corning Fiberglas Corp., Newark, Ohio. (Richard Lund, Battelle Memorial Institute, 505 King Ave., Columbus, Ohio).

District 5: R. D. Satterley, Inland Steel Co., Ishpeming, Mich.

District 6: Lincoln F. Elkins, Sohio Petroleum Co., 1300 Skirvin Tower, Oklahoma City, Okla. (H. D. Christner, Continental Oil Co., P. O. Box 795, Oklahoma City, Okla.).

District 7: D. H. Beetem, Aluminum Co. of America, P. O. Box 120, Vancouver, Wash.

District 8: T. G. Chapman, College of Mines, Univ. of Arizona, Tucson, Ariz.

District 9: D. E. Hewitt, Box 472, Brownfield, Texas (Gus Athanas, Box 278, Lubbock, Texas).

District 10: V. C. Perini, Jr., Box 840, Abilene, Texas. (Joseph B. Jenkins, Stanolind Oil & Gas Co., Box 120, Abilene, Texas).

INVESTIGATION of VARIOUS REFINED OILS for FORMATION FRACTURING

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ABSTRACT

The properties of some of the common fracturing oils, such as sand-falling rate, fluid loss and viscosity, are a function of the three major constituents of the oil. These are: asphaltic material, paraffin waxes and a base oil. The base oil can be either high or low viscosity.

Asphaltic material increases viscosity by thickening the oil, decreasing the rate of fall of sand through the oil, at temperatures up to 200° F.

When large amounts of paraffin wax are present, much of the wax is not dissolved, but is present in the form of microscopic crystals. This, of course is limited to temperatures below the melting points of waxes. As a result, paraffin waxes do not function primarily as thickeners, but rather as bulking materials.

The function of wax, without asphaltic material, in a low viscosity base oil is uniquely unlike that of wax with asphalt coexistent in the oil. The resulting difference in wax crystal size governs the sand-falling rate to a large extent.

An ideal type of fracturing oil is one containing neither asphalt nor waxes. In such cases, the viscosity and resulting low sand-falling rate are apparently due to soluble resinous hydrocarbons, which are compatible with formation oils.

Revised manuscript received on Oct. 24, 1955. Paper presented at AIME Annual Meeting in New York City Feb. 13-17, 1955.

INTRODUCTION

Since the introduction of hydraulic fracturing as a method of stimulating production from oil and gas wells, a variety of fluids have been employed to open the fractures and carry the propping agent. Such fluids include gels, emulsions, and oils. In the latter category, the use of refined oils has increased tremendously, and it is probably safe to assume that such oils represent more than one-half of the total fluid used in fracturing.

The general acceptance of refined oils for fracturing can be accounted for on the basis of their relatively low cost and general applicability. To minimize transportation costs, such refined oils are generally obtained within the local areas of operation. As a result there are several kinds of oil used in different areas, with a wide variation in the basic composition. These types may vary from a fair grade of lubricating stock to a highly viscous cut-back asphalt, or road oil.

Originally, little attention was paid to the composition of the oils used for fracturing, and any oil which would carry sand was considered satisfactory. Recently, however, service companies and well operators have become more concerned with the type of oils used for fracturing. With this in mind, the present work was undertaken to evaluate and compare many widely used fracturing oils to determine which constituents were most desirable for fracturing purposes.

Some of the important properties of fracturing fluids are sand-falling rate, viscosity, and fluid loss. Other properties, that are actually of no less importance, include flash point, pour point, emulsifying tendencies with formation brines, and compatability with the formation oils. This discussion has been limited, however, to the first mentioned properties in order to give some idea of the general composition of the refined oils, how they function, and why.

PROPERTIES OF FRACTURING OILS

The properties of fracturing oils are a function of the three major constituents of the oil. These may be designated as: (1) asphaltic material, (2) paraffin waxes and (3) a base oil, which may be of either high or low viscosity. The asphaltic material clas-

TABLE 1 — ANALYSIS OF TYPICAL FRACTURING OIL WITH REGARD TO ASPHALT AND WAX CONTENT

Oil	% Total Asphalt[1]	% Asphaltene[2] (in asphalt fraction)	% Wax[2]	% Base Oil
A	33	5	3	64
B	30	2.2	21	49
C	5	trace	trace	95
D	17	3.1	10	73
E	20	1.1	33	47

[1]Distillation Residue at 360°C (10 mm pressure)
[2]Precipitation with 10:1 Pentane (85°F)
[3]Dewaxed with Acetone dilution 7:1 (32°F)

sification, for the purpose of this paper, includes any high molecular weight naphthenic constituents in the oil. The variation in the composition of different fracturing oils is indicated by the data shown in Table 1.

Low as well as high percentages of both asphalts and waxes are found in various oils. In Table 1, the second column indicates the total asphaltic material present in the oil, while the third column shows the percentage of asphaltene materials present in this fraction; the fourth column indicates the high molecular weight paraffinic material present; and the percentage of base oil present is shown in the fifth column. (This base oil consists of low molecular weight naphthenic materials and paraffins.)

The effect of the various constituents on the viscosity of the oil is illustrated in Table 2. In order to keep the phenomenon of gel strength from interfering with measuring actual viscosities, the latter were determined by an Ultra-Viscoson (Model XV, Rich-Roth Laboratories). Viscosities in the column headed Distillate show the effect on viscosity of removing the asphaltic material. Figures in the Base Oil column represent the viscosities of the base oils, after both asphalts and wax have been removed. It can be seen from Tables 1 and 2 that Oil A achieves its viscosity almost entirely from asphaltic material. Oil C, by contrast, achieves its viscosity mainly from the use of a highly viscous base oil.

The viscosity of most fracturing oils with various fractions omitted demonstrates that an oil of low viscosity is usually used as a base, when appreciable amounts of either asphalt or wax are used in compounding a fracturing oil. With asphalts and waxes present in only small amounts, a low sand-falling rate is achieved by using a high viscosity base oil, similar to the heavy weight lubricating oils. Sand-falling rate is usually measured by observing the rate at which graded sand, 20-40 mesh, falls through the oil.

This is generally considered to be related to the viscosity of the fluid. A low rate is of importance for a fracturing oil since the sand must remain suspended in the oil during the treatment. A rate of 5 ft/minute or less has been found satisfactory for current pump capacities. The sand-falling rate in water, for comparative purposes, is approximately 27 ft/minute. As pointed out later, it has been observed that there is not necessarily a direct relationship between viscosity and sand-falling rate.

TABLE 2 — VISCOSITY* (CP @ 80°F) OF FRACTURING OILS

Oil	Original Oil	Distillate (asphalt removed)	Base Oil (asphalt and wax removed)
A	215	14	13
B	184	31	20
C	215	190	185
D	200	45	35
E	124	60	17

*Viscosity measured on Ultra-Viscoson.

Asphaltic Material

Asphalts or asphaltic material are usually present in the form of micelles, or aggregates of macro-molecules within the oil base. The asphaltic material reduces the sand-falling rate by two methods. In addition to increasing the viscosity of the base oil, the micellular aggregates of asphalt further decrease the sand-falling rate by a bulking action. It appears probable that this bulking action results from the physical dimensions of the micelles.

Asphaltenes are oxidized high molecular weight polycyclic aromatic hydrocarbons. They are not actually soluble in oil. According to Sachanen[1], the insoluble asphaltenes readily adsorb resins and aromatic hydrocarbons and are dispersed in the oil. Thus, the resins and aromatic hydrocarbons colloidally protect the asphaltenes, as all three materials exist as miscelles in equilibrium with the hydrocarbon constituents of the oil. The resistance offered by these micelles serves to slow the fall of the sand particles.

The asphaltic miscelle effect is represented graphically in Fig. 1, showing the viscosity-sand-falling rate relationship. The curve of an oil of Newtonian properties, containing no asphalt, follows a nearly straight line function. The effect of asphalt is to impart lower sand-falling rates to a base oil of comparable measured viscosity. For a specific viscosity, the sand-falling rate of the blended oil is lower than that of the base oil (a true solution). An oil with a low sand-falling rate and low viscosity might be of advantage since friction pressures encountered during a fracture treatment using such an oil would be lower than when using a base oil with equal sand-falling rate.

The effects of asphaltic material are not all favorable, however. Refineries and pipeline companies are becoming more concerned with the dilution or contamination of crude oils with "foreign fluids" such as fracturing oils. This concern for compatability, in many cases, stems from the use of asphaltic fracturing oils. The colloidally dispersed asphaltenes

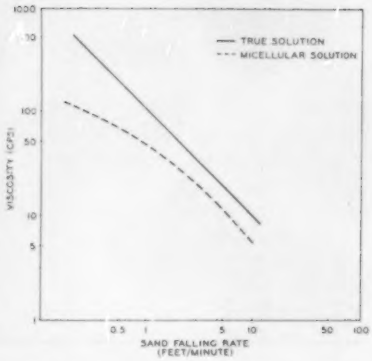

FIG. 1 — MICELLE EFFECT OF ASPHALT IN OIL.

may be precipitated upon dilution with crude oils. This is especially true for high gravity crudes. When the fracturing oil is diluted, the resins and aromatic hydrocarbons tend to dissolve, the micelle equilibrium is destroyed, and the asphaltenes coagulate and precipitate. The precipitation of a crude asphalt can be extremely troublesome, so far as plugging and fouling tubing and lines is concerned.

Some refinery processing includes the use of propane dilution for asphalt removal. This same precipitation as a result of dilution, may occur during a fracture treatment. A highly asphaltic fracturing oil could, therefore, plug the flow channels of a formation and offset any advantage gained as a result of the fracturing treatment.

Paraffin Waxes

Whereas asphaltic materials are usually present in the form of micellular aggregates, paraffin waxes, present in the oil, exist either in solution or in the form of wax crystals. Such wax crystals in the refined oil used for fracturing treatments, display a bulking effect which, in certain respects is similar to asphalt. The crystals of wax delay the fall of the sand particles without increasing the actual viscosity of the base oil. Fig. 2 demonstrates and compares this effect. The curve representing fracturing oil with paraffin wax is more divergent than that for the asphaltic oil, since the waxes have a definite melting or crystallization range. Above the melting point, the wax effect does not function; therefore, the curves coincide. To further illustrate this point Fig. 3 shows the effect on sand-falling rate, at various temperatures, of the various components of a typical fracturing oil (Oil E).

[1] Reference given at end of paper.

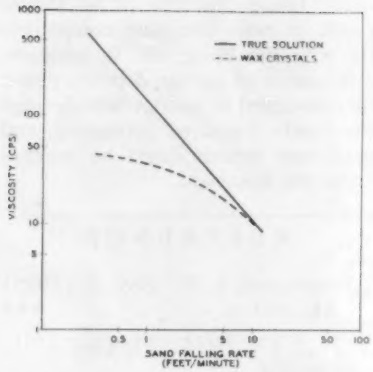

FIG. 2 — CRYSTAL EFFECT OF WAX IN OIL.

The size of the wax crystals has a unique role in the characteristic property of sand-falling rate control. The presence of asphalt with the wax in the oil results in a smaller particle size than that obtained without the asphalt present. Apparently the wax particles become coated with the resinous asphalt, and are thus restricted from material growth. Fig. 4 shows three photo micrographs: one of an asphaltic, wax-base, fracturing oil; and the second of the base oil fraction, with the asphaltic material removed. By omitting the asphalt, the wax crystals were 2 to 3 times as large. This increase in crystal size actually reduced the sand-falling rate, although the viscosity was decreased by the omissions of the asphalt portion. As the third photo micrograph shows, addition of the asphalt, with heating and recooling, caused a reduction in crystal size of the wax particles, increasing both the viscosity and the sand-falling rate.

A refined oil that is high in paraffin waxes could be a source of trouble if used as a fracturing fluid for low temperature wells. In wells with temperatures below the melting points of the waxes, it is possible that wax deposits might plug the flow channels. Wax deposits also might plug tubing and lines, or accumulate in tank batteries.

Wax particles, as well as asphaltenes, are hydrophobic in nature. Because of this, these materials have been observed to stabilize water-in-oil type emulsions. This is not of too much importance in most fracturing treatments; however, it should be considered since, in isolated instances, emulsion troubles do plague recovery operations. The absence of both wax and asphaltic material in the fracturing oil should prevent aggravating any potential emulsion problem.

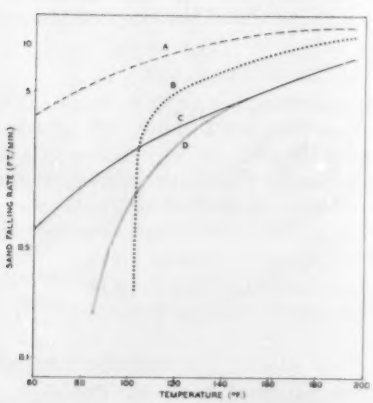

FIG. 3 — EFFECT OF VARIOUS COMPONENTS ON SAND-FALLING RATES OF OIL.

FLUID LOSS

Another important property in a fracturing oil is fluid loss. If the loss of the fracturing oil into the formation is too great, sufficient pressure build-up to open a fracture is difficult to obtain. If most of the oil was lost into the formation while the fracture is created, the sand would have no carrying media.

Low fluid loss in a fracturing oil may be accomplished in two ways: (1) by incorporating a plugging material into the oil, and (2) by increasing the viscosity of the oil. Asphaltic micelles, which are actually insoluble, as well as wax crystals, show a tendency to plug formation pores, reducing fluid loss. As a rule, fluid loss reduction by this type of plugging is not desirable, as the plugging materials may be difficult to remove from a formation. This, of course, could be detrimental, in a fracturing treatment. The reduction of fluid loss by increasing the viscosity of the fracturing oil, on the other hand, avoids plugging of formation pores.

Fluid loss properties of a fracturing oil are, in part, a function of relatively insoluble asphalts as shown by the data in Table 3. It would appear that the asphalts are not completely dissolved and therefore tend to plug, thereby reducing the loss of fluid. This plugging effect, that occurs at the face of a formation during a fracturing treatment, would tend to minimize contamination within the formation itself. The amount of insolubles governs, to a large extent, the penetration of the fluid into the formation flow channels. The asphalts could then precipitate, resulting in a decrease in potential productivity. The extent of precipitation will depend on the nature of the native oil in the formation. Formation crude containing large amounts of light ends will precipitate more asphaltic material from a fracturing oil than a crude with small amounts of light fractions.

CONCLUSIONS

In summation, the three major constituents of refined oils used as fracturing fluids, may function in several ways. The asphalts, waxes, and base oil individually and collectively affect the viscosity, sand-falling rate, fluid loss, and compatibility of the oil with produced crude oils. Asphaltenes, in the asphaltic portion, and wax crystals impart low sand-falling rates at lower viscosities than would be required for a base oil, alone. A significant disadvantage of the asphalt and wax is their tendency to plug minute flow channels, and to contaminate produced crude by precipitation of insolubles, when diluted in the formation. To induce low fluid loss by the use of plugging materials is not necessarily harmful, if the material used to accomplish

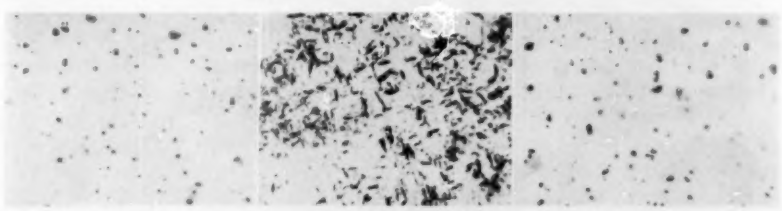

FIG. 4 — EFFECT OF ASPHALT CONTENT ON THE SIZE OF WAX CRYSTALS IN REFINED OIL USED FOR FRACTURING TREATMENTS (200 X MAGNIFICATION).

TABLE 3—EFFECT OF CONSTITUENTS OF A FRACTURING OIL ON FLUID LOSS

Composition: 15% Asphalt, 20% Wax, 65% Base Oil (20 cp at 80° F measured with Ultra-Viscoson)

Test	Fraction of Oil	Fluid Loss (API Code 29) @ 80° F	Fluid Loss (API Code 29) @ 200° F
1	Original oil	75 ml/30 min	100 ml/30 min
2	with asphalt removed	70 ml/30 min	400 ml/2 min
3	with wax removed	75 ml/30 min	90 ml/30 min
4	w/wax & asphalt removed	400 ml/4 min	400 ml/2 min
5*	High Viscosity base oil (no asphalt, no wax)	400 ml/13 min	400 ml/5 min

*Viscosity of 140 cp at 80° F (Ultra-Viscoson)

this is easily removed by dissolution, decomposition, or other assured means. Removal is usually difficult to accomplish in the case of asphalts and waxes.

The most satisfactory refined oils for use in fracturing should be ones without appreciable amounts of waxes, and especially asphaltic material. A more desirable fracturing oil would be one whose viscosity, sand-falling rate, and possibly fluid loss are a function of the base oil itself. Using this type of oil should result in more complete compatibility with the crude oil. In addition, a minimum of foreign deposits would be introduced to restrict flow through the newly fractured formation, and maximum benefit could be realized from the treatment.

REFERENCE

1. Sachanen, A. N.: *Petr. Z.* (1925) **21,** 1441.

★★★

SOME USEFUL TABLES for APPROXIMATING SMOOTH CURVES by FIFTH-AND-LOWER DEGREE POLYNOMIALS

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INTRODUCTION

The use of computing machines to solve physical problems has made it imperative to represent physical data in a form computing machines can use. Although curve-fitting is an old and well-practiced art, there still seems to be some interest in questions regarding what methods can be used and why. Even though there are many good references on this subject, it may be of some value to discuss a particular method which has been found to be useful, and to make available the associated tables for its use in the hope that there can be saved a few of the tedious hours necessary to reduce many of the suggested methods to practice. Although a very brief discussion of the mathematical background of the tables is included immediately below, those interested only in their use can skip directly to the section on Use of the Tables.

DIRECT FIT OF A SET OF POINTS

A frequently encountered problem is: Given data which can be represented by a smooth curve $\phi(x)$, to find an easy-to-evaluate function $F(x)$, with only a few coefficients, which is a good approximation of $\phi(x)$ on the interval $0 \leq x \leq x_n$. Consider $F(x)$ as a linear combination of $m + 1$ arbitrary, single-valued, continuous, linearly independent functions, $f_i(x)$,

$$F(x) = a_0 f_0(x) + a_1 f_1(x) + \ldots + a_i f_i(x) + \ldots + a_m f_m(x) \quad \ldots\ldots\ldots \quad (1)$$

If the value of $\phi(x)$ is known or can be read from the curve at the points x_j: $\phi(x_0)$, $\phi(x_1)$, $\ldots$ $\phi(x_j)$ $\ldots$ $\phi(x_n)$, and if $n = m$, then all the coefficients of $F(x)$ can be determined, and $F(x_j) - \phi(x_j) = 0$ for $j = 0, 1, \ldots n$. This follows from the solution of the set of linear simultaneous equations.

$$\begin{aligned}
\phi(x_0) &= a_0 f_0(x_0) + a_1 f_1(x_0) + \ldots + a_m f_m(x_0) \\
\phi(x_1) &= a_0 f_0(x_1) + a_1 f_1(x_1) + \ldots + a_m f_m(x_1) \\
\phi(x_n) &= a_0 f_0(x_n) + a_1 f_1(x_n) + \ldots + a_m f_m(x_n) \\
&\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)
\end{aligned}$$

for the coefficients a_i.

Although the set a_i from the solutions of the set of Equations 2 yields an $F(x)$ which gives an *exact* value of $\phi(x_j)$ for the $n + 1$ points, there is no restraint on $F(x)$ in the interval $x_j < x < x_{j+1}$. Indeed, if the points $\phi(x_j)$ are not sufficiently smooth, very serious differences may arise between $F(x)$ in the interval and the smooth curve $\phi(x)$.

LEAST-SQUARES FIT

It has been suggested[1] that if n is made to exceed m, and the set a_i is found to minimize the function

$$\psi(a_0, a_1, \ldots a_m) = \sum_{j=0}^{j=n} [F(x_j) - \phi(x_j)]^2,$$

the function $F(x)$ is much less sensitive to small errors in $\phi(x_j)$, and usually provides a much better fit to the smooth function $\phi(x)$. This is known as the best fit in the sense of the least-squares error.

To minimize ψ, set

$$\frac{\partial \psi}{\partial a_i} = 0, i = 0, 1, \ldots m, \quad \ldots\ldots \quad (3)$$

The $m + 1$ equations from Equation 3 are

$$a_0 \sum_{k=0}^{k=n} f_0(x_k)\, f_i(x_k) + a_1 \sum_{k=0}^{k=n} f_1(x_k)\, f_i(x_k) + \ldots + a_m \sum_{k=0}^{k=n} f_m(x_k)\, f_i(x_k) = \sum_{k=0}^{k=n} \phi(x_k)\, f_i(x_k), \quad \ldots\ldots \quad (4)$$

one equation being obtained for each $i = 0, 1, \ldots m$. Inasmuch as the arbitrary functions $f_i(x)$ may be evaluated for x_k, $k = 0, 1, \ldots n$, and the $\phi(x_k)$ are known values of the curve to be fitted, the simultaneous Equations 4 may be solved for the set a_i.

PARTICULAR FUNCTIONS

Given the functions $f_i(x)$ and the set $\phi(x_j)$, the solutions for a_i require evaluating a number of sums of products as well as the solution of an $m + 1$ order set

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*W. P. Schultz is now with Core Laboratories, Inc., Dallas.

[1]Reference given at end of paper.

of simultaneous equations. Much of the work can be done once and for all if there is chosen a standard set of $f_i(x)$ for the approximating functions and a standard set of (x_j) where ϕ is to be approximated. Then the Equation 4 can be solved for the set a_i to give the solutions

$$a_i = \sum_{j=0}^{j=n} b_{ij}\,\phi(x_j),\ i = 0, 1, \ldots m, \quad . \quad (5)$$

requiring at most $m + 1$ sums of $n + 1$ products to evaluate all the coefficients in $F(x)$ for a given set $\phi(x_j)$.

The validity of Equation 5 may be seen most easily by the use of matrix notation. Equation 4 may be written as

$$[D]\vec{a_i} = [G]\vec{\phi(x_j)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where the element of $[D]$ is $d_{p,q} = \sum_{k=0}^{k=n} f_q(x_k)\, f_p(x_k)$, the element of [G] is $g_{p,q} = f_p(x_q)$, $\vec{a_i}$ is the column vector of $m + 1$ coefficients, and $\vec{\phi(x_j)}$ is the column vector of $n + 1$ values from the curve $\phi(x)$. Premultiplying Equation 6 by $[D]^{-1}$ gives

$$\vec{a_i} = [D]^{-1}\,[G]\vec{\phi(x_j)} = [B]\vec{\phi(x_j)}, \quad . \quad . \quad (7)$$

which is equivalent to Equation 5 where the coefficients b_{ij} are the elements $b_{p,q}$ of the matrix $[B] = [D]^{-1}\,[G]$ of Equation 7.

Numerical Values for [B]

The functions $f_i(x)$ were chosen as $f_i(x) = x^i$ and the interval $0 \leq x \leq 1$ was divided into 10 equal parts by the set $x_j = j/10$, $j = 0, 1, \ldots 10$. Tables 1 through 5 present the numerical values of the elements of $[B]$ for $m = 1, 2, 3, 4$, and 5, respectively. An estimate of the precision of the individual elements has not been made, but tests with simple functions, e.g., $y = x$, $y = c$, yield approximations which are better than one part in 10,000.

Use of the Tables

This description is included to assist readers who have no taste for the foregoing discussion but who, nonetheless, should like to fit graphical data with polynomials of degree five, or lower.

Given a smooth curve y as some function of x, an interval on the x-axis must be selected for which the curve $y(x)$ is to be fitted. By translation of the origin and change of scale, the interval along the x-axis must be made to be $0 \leq x \leq 1$. This interval must be divided into 10 sub-intervals by 11 equally spaced points, $x = 0$, 0.1, 0.2 . . . 1.0, and the 11 corresponding values of y must be read off the curve $y(x)$. Now the coefficients of a polynomial to approximate ϕ in the interval can be obtained using the appropriate table.

Consider finding the coefficients of the third degree polynomial

$$F(x) = a_0 + a_1x + a_2x^2 + a_3x^3$$

by use of Table 3 and the 11 points from a curve $y(x)$. The value of a_0 is found as the sum of the products of the 11 values on the top (x^0) line of Table 3 with the 11 values of $y(x)$ taken from the curve at the points of x corresponding to the values in the heading of the tables. The value of a_1 is found similarly by using the second (x^1) line of Table 3. The polynomial with the four coefficients evaluated by using Table 3 in this way is the unique third degree polynomial which minimizes the sum of the squares of the 11 differences between the value of the polynomial at the points $x = 0$, 0.1, 0.2, . . . 1.0 and the y-values used in forming the sums of products.

It might be well in conclusion to point out that many smooth curves $y(x)$ are not approximated well by polynomials. It is always advantageous to evaluate the polynomial at the 11 input points to check the closeness of fit. In the event $y(x)$ is not approximated well by a polynomial, log y, y^n, or some other easily evaluated function of y may yield a better fit. Judgment and experience will help in selecting the best function of y to use.

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★★★

TABLES 1-5 — NUMERICAL VALUES OF ELEMENTS OF [B] FOR m = 1, 2, 3, 4, and 5, RESPECTIVELY

x =	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
						I					
a^0	0.31818182	0.27272727	0.22727273	0.18181818	0.13636364	0.09090909	0.04545455	0	-0.04545455	-0.09090909	-0.13636364
a^1	-0.45454545	-0.36363636	-0.27272727	-0.18181818	-0.09090909	0	0.09090909	0.18181818	0.27272727	0.36363636	0.45454545
						II					
a^0	0.58041958	0.37762238	0.20979021	0.07692308	-0.02097902	-0.08391608	-0.11188811	-0.10489510	-0.06293706	0.01398602	0.12587413
a^1	-2.20279720	-1.06293706	-0.15617715	0.51748252	0.95804196	1.16550117	1.13986014	0.88111888	0.38927739	-0.33566434	-1.29370630
a^2	1.74825175	0.69930070	-0.11655012	-0.69930070	-1.04895105	-1.16550117	-1.04895105	-0.69930070	-0.11655012	0.69930070	1.74825175
						III					
a^0	0.790210	0.335664	0.055944	-0.083916	-0.118881	-0.083916	-0.013986	0.055944	0.090909	0.055944	-0.083916
a^1	-5.536131	-0.396270	2.288267	3.073038	2.513598	1.165501	-0.415695	-1.674437	-2.055167	-1.002331	2.039627
a^2	10.489510	-1.048951	-6.526806	-7.400932	-5.128205	-1.165501	3.030303	6.002331	6.293706	2.447552	-6.993007
a^3	-5.827506	1.165501	4.273504	4.467754	2.719503	0	-2.719503	-4.467754	-4.273504	-1.165501	5.827506
						IV					
a^0	0.916088	0.209791	-0.069930	-0.104896	-0.034965	0.041956	0.069930	0.034965	-0.034965	-0.069930	0.041956
a^1	-9.906823	3.974339	6.658913	3.801495	-0.400146	-3.205116	-3.329441	-0.945999	2.315465	3.368307	-2.330994
a^2	32.342712	-22.803078	-28.379969	-11.043142	9.440552	20.687627	17.599063	2.360142	-15.559437	-19.405598	14.860128
a^3	-40.792541	36.130538	39.238541	10.295260	-20.590523	-34.965031	-26.029529	1.359748	30.691527	33.799532	-29.137522
a^4	17.482518	-17.482518	-17.482518	-2.913752	11.655012	17.482518	11.655012	-2.913752	-17.482518	-17.482518	17.482518
						V					
a^0	0.973771	0.094415	-0.089159	-0.027978	0.041952	0.041952	-0.006987	-0.041952	-0.015730	0.045446	-0.015730
a^1	-14.428829	13.018550	8.166224	-2.228024	-6.429619	-3.205087	2.700070	5.083487	0.808051	-5.675974	2.191151
a^2	69.600090	-97.416930	-40.799092	38.633413	59.117073	20.687646	-32.077492	-47.316429	-3.140214	55.109307	-22.397372
a^3	-145.75444	246.05414	74.225850	-129.65370	-160.53948	-34.965035	113.91956	141.30869	-4.296017	-176.12417	75.824619
a^4	137.66779	-257.85294	-57.544256	157.33315	171.90190	17.482476	-148.59201	-163.16058	22.579454	222.88802	-102.70301
a^5	-48.074109	96.148218	16.024703	-64.098812	-64.098812	0	64.098812	64.098812	-16.024703	-96.148218	48.074109

TECHNICAL NOTE 319

THE CONDUCTION of HEAT INCIDENT to the FLOW of VAPORIZING FLUIDS in POROUS MEDIA

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INTRODUCTION AND PURPOSE

Problems relating to thermal methods of oil recovery have been given increasing attention during the past year. The nature of the physical and chemical processes underlying thermal recovery are not yet well understood. The need for pertinent basic information is recognized generally. One of the processes involved is the transfer of heat by conduction in oil reservoir rocks containing moving reservoir fluids. This technical note deals with heat conduction in a laboratory sand column filled with a moving hydrocarbon and therefore should be contributory to the presently inadequate fund of knowledge on the over-all subject.

In an analysis of the flow of vaporizing propane through a horizontal column of sand, one of the present authors[3] demonstrated correspondence between the measured values of pressure along the length of the column and those predicted by a theory which postulated that the enthalpy of the propane was invariable along the length of the column. This postulate was implied as a deduction from the principle of conservation of energy but the details of the deduction were not given. The specific purpose of this technical note is the presentation of these details both as an adjunct to the earlier analysis and to supply some additional details on the processes involved in this type of flow. Results disclose that rates of heat transfer by conduction, in the direction of fluid motion, generally would be small for systems of the type studied.

FUNDAMENTAL ENERGY EQUATION

The principle of conservation of energy may be applied to a section of the porous material on the basis that heat transfer, like fluid flow, is possible in the x direction only. Transfer of heat in the y and z directions is prevented by suitable insulation or by taking the medium as infinite in directions perpendicular to the x axis. For steady state heat conduction and conditions of steady fluid flow the principle of conservation of energy specifies that any reduction in the enthalpy rate increases the flow of heat in the same proportion. Stated mathematically,

$$\frac{dH}{dx} = \frac{KA}{W}\frac{d^2T}{dx^2} \quad \ldots\ldots\ldots\ldots \quad (1)^*$$

where $-\frac{KA}{W}\frac{dT}{dx}$ is the flow of heat in the positive x direction.

TEMPERATURE DISTRIBUTION IN DIRECTION OF FLOW

The column of sand used in the previously described research is divisible into three different flow regimes, each of which may be analyzed independently. In the entrance region the liquid approaches the saturation state. A transition region is postulated following the transverse section at which the saturation state of the liquid is attained. In this transition region gas and liquid phases are both envisioned as present, with no vaporization occurring and with fluid movement restricted to the liquid. The upstream end of the exit region is at the transverse section of the column where the fraction of the pore space occupied by gas first becomes great enough for gas flow and where vaporization of the liquid begins. Fig. 1 indicates schematically the thermodynamic processes undergone by the fluid in the three flow regimes.

[3]References given at end of paper.
Original manuscript received on Oct. 28, 1953. Revised manuscript received on Nov. 14, 1955.

*A nomenclature list appears at the end of paper.

Entrance Region

The relation between the enthalpy of the flowing fluid and the pressure and temperature of this fluid is given by

$$dH = -\eta c_p dP + c_p dT \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Equation 2 is applicable regardless of whether the flowing fluid exists as a gas, a liquid, or as a gas-liquid mixture. Liquid is the only fluid phase present in the entrance region.

In this analysis the effect of the pressure on the enthalpy of this liquid is neglected, so that $dH = c_p dT$ is assumed to apply in the entrance region. If this value is substituted for dH in Equation 1 and the result integrated with the boundary conditions specified as $T = T_o$ at $x = 0$ and $\frac{dT}{dx} = \left(\frac{dT}{dx}\right)_1$ at $x = x_1$, the temperature distribution for the entrance region will be found to be

$$T = T_o + \left(\frac{dT}{dx}\right)_1 \left(\frac{e^{ax} - 1}{ae^{ax_1}}\right) \quad . \quad . \quad . \quad . \quad (3)$$

Transition Region

In the original paper[2] the boiling point at x_1 was considered to be a mathematical sheet where vaporization began and the pressure gradient became discontinuous, the ratio of this gradient at the upstream side of the boiling front to that at the downstream side being estimated as equal to $(k_L/k)_o$, or about 0.8. This concept of the boiling front was based on the conclusions of Wyckoff and Botset[5] regarding their critical "equilibrium gas saturation." Accordingly, the gas content at x_1 would be taken as this equilibrium value, but an anomaly results.

Vaporization occurs if both phases are flowing, and then $c_p \to \infty$. If only the liquid is flowing c_p is finite, however, and refers to liquid approaching the saturation state. As gas and liquid are both present in the postulated transition region, even though only one is flowing, Equation 2 may be written $\frac{dP}{dx} = \eta \frac{dT}{dx}$, in which η is the slope of the vapor pressure curve. Thus, any discontinuity in the pressure gradient would be reflected in the temperature gradient. But a discontinuity in the temperature gradient is not plausible, because the rate of heat transfer by conduction is proportional to $-\frac{dT}{dx}$ and the energy-balance basis of Equation 1 reveals no heat sources that could bring about abrupt changes in $\frac{dT}{dx}$. For this reason and as attainment of the critical equilibrium gas content over zero length of sand column is not tenable physically, the gas content is assumed to increase gradually in the direction of fluid motion from zero at x_1 to the critical equilibrium value at x_2, a finite distance farther downstream.

As no gas moves within the transition region, Fig. 1 depicts the thermodynamic process within this region and the saturated liquid line as coincident. Thus, the mass fraction of gas in the *flowing* stream is represented correctly as zero even though the *in-place* gas content is finite, this gas having been formed during the transient flow period preceding the establishment of steady flow.

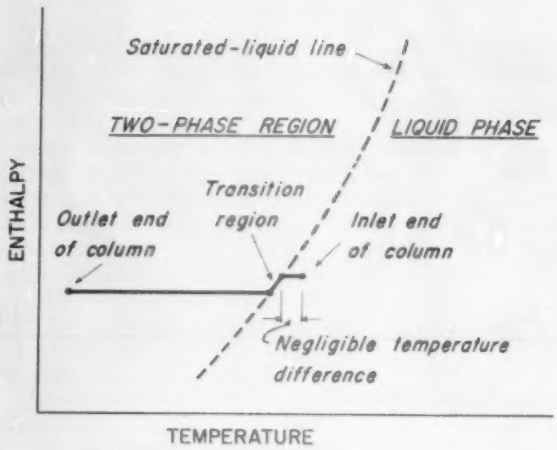

Fig. 1 — Thermodynamic Processes Undergone by a Single-Component Fluid That Vaporizes While Moving Through a Column of Thermally-Isolated Porous Medium.

Darcy's law, the saturation relation of pressure and temperature, and the transition region concept indicate that at x_1

$$\frac{1}{\eta}\left(\frac{dT}{dx}\right)_1 = \left(\frac{dP}{dx}\right)_1 = -\frac{W\mu\bar{v}}{kA} \quad . \quad . \quad . \quad . \quad (4)$$

The first and last members of Equation 4 may be used to evaluate $\left(\frac{dT}{dx}\right)_1$ and the result substituted in Equation 3 to give the temperature difference between the inlet end of the column and x_1:

$$T_o - T_1 = \eta_1 \left(\frac{W\mu\bar{v}}{kA}\right)\left(\frac{e^{ax_1} - 1}{ae^{ax_1}}\right) \quad . \quad . \quad . \quad (5)$$

The pressure difference over the same length of column is given by integration of Darcy's law:

$$P_o - P_1 = \left(\frac{W\mu\bar{v}}{kA}\right)x_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The length x_1 of the entrance region in which subcooled liquid moves is that which satisfies Equations 5 and 6 in conjunction with the saturation relation $P_1 = P_1(T)$.

In the transition region all states are saturation states and the presence of stationary gas results in the permeability of the sand to liquid being reduced from k at x_1 to about 0.8 k at x_2. Because of the saturation condition and because $dH = c_p\, dT$ for liquid, approaching the saturation state Equation 1 may be written

$$\frac{dP}{dx} = \frac{KA}{Wc_p}\frac{d^2P}{dx^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and differentiating Darcy's law for the liquid with respect to x gives

$$\frac{d^2P}{dx^2} = \frac{W\mu\bar{v}}{Ak_L^2}\frac{dk_L}{dx} = -\frac{1}{k_L}\frac{dP}{dx}\frac{dk_L}{dx} \quad . \quad . \quad . \quad (8)$$

If the righthand side of Equation 8 is substituted for $\frac{d^2P}{dx^2}$ in Equation 7 and the result integrated the length of the transition region is found to be

$$x_2 - x_1 = \frac{KA}{Wc_p} ln \frac{(k_L)_1}{(k_L)_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where $ln\,[(k_L)_1/(k_L)_2] \approx 0.22$.

EXIT REGION

The vaporization which begins at x_2 initiates the exit region in which the fluid flows in two phases. In this region the enthalpy of the flowing mixture is given by

$$WH = W_G H_G + W_L H_L \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Integration of Equation 1 with the boundary conditions specified as $H = H_2$ when $\left(\frac{dT}{dx}\right) = \left(\frac{dT}{dx}\right)_2$ yields

$$WH = KA\left[\frac{dT}{dx} - \left(\frac{dT}{dx}\right)_2\right] + WH_2 \quad . \quad (11)$$

Equating the righthand sides of Equations 10 and 11 to each other and setting $W_G = fW$ and $W_L = (1 - f)\,W$, results in the energy equation for the exit region:

$$fH_G + (1 - f)\,H_L = \frac{KA}{W}\left[\frac{dT}{dx} - \left(\frac{dT}{dx}\right)_2\right] + H_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Darcy's law for the exit region, in terms of the quantity F used in the original presentation, may be stated $\frac{dP}{dx} = -\frac{W}{AkF}$, and within this region $\frac{dT}{dx} = \eta \frac{dP}{dx}$.

Hence, Equation 12 may be put into the form

$$f = \frac{H_2 - H_L}{H_G - H_L}\left[1 - \frac{K\eta\left(\frac{1}{F} - \frac{1}{F_2}\right)}{H_2 - H_L}\right] \quad . \quad (13)$$

When the second term in brackets approaches zero, Equation 13 approaches that which would apply for isenthalpic flow.

APPLICATION OF RESULTS

Data pertaining to "Experiment V" of the earlier paper are: $W = 2.9 \times 10^{-3}$ lb sec^{-1}; $k = (k_1)_1 = 1 \times 10^{-11}$ ft^2; $A = 2.0 \times 10^{-2}$ ft^2; $(k_L)_2 \approx 0.8\ (k_L)_1$; $K = 2.4 \times 10^{-4}$ Btu sec^{-1} ft^{-1} °F^{-1} (Herbert et al[2]). The properties of the sub-cooled propane approaching the saturation state at x_1 were $\eta = 3 \times 10^{-6}$ °F lb^{-1} ft^{-2} (Sage et al[4]); $(\mu\bar{v})_1 = 6.2 \times 10^{-6}$ ft sec; $c_p = 0.68$ Btu lb^{-1} °F^{-1} (Sage et al[4]). As per Fig. 3 of the earlier paper, $\eta = 3 \times 10^{-3}$ °F lb^{-1} ft^{-2} for the regions of the system in which the propane existed in two phases, and according to Fig. 6, F and F_2 were of the order of 5×10^6 ft^{-1} sec^{-1} and 13×10^6 ft^{-1} sec^{-1}, respectively; $H_2 - H_L$ was of the order of 10 Btu lb^{-1}.

Inspection of Equation 5 with the appropriate numerical data indicates that the quantity a was so large (4.1×10^2 ft^{-1}) that the reduction in temperature in the entrance region was negligible, and the postulate of isothermal flow in that region sustained.

Equation 9 indicates that the length of the transition region was 5.4×10^{-4} ft or approximately equal to the size of the openings in the No. 80 sieve of the Standard Tyler Sieve Scale. About half the sand comprising the column in the propane flow experiments was coarser than Tyler No. 80, so that the computed length of the transition region probably did not exceed at most a few pore diameters. Neglect of this region in the earlier paper therefore was justified, although the comments made there regarding discontinuities in the pressure gradient were not justifiable in the limit.

Finally, the second term in brackets in Equation 13 may be computed with the foregoing numerical data to be of the order of 0.001, which is negligible.

These numerical calculations disclose that the heat conductive effect in the propane flow experiments was of no appreciable consequence.

The energy-balance principles applied mathematically in this note would apply also to multicomponent fluid flow systems. Research on such systems, as an extension of the present work, appears desirable in the interest of gaining a better understanding of heat transfer in oil reservoirs.

NOMENCLATURE

x = distance along column of porous medium
Q = rate of heat transfer by conduction
W = weight rate of flow of gas plus liquid
K = thermal conductivity of fluid-filled porous medium
A = bulk cross-sectional area of column of porous medium
T = absolute temperature
H = enthalpy per unit weight of fluid
η = Joule-Thomson coefficient (also slope of vapor pressure curve)
c_p = heat capacity at constant pressure
P = fluid pressure
μ = absolute viscosity
$\bar{v}$ = specific volume
k_G = effective permeability to gas
k_L = effective permeability to liquid
k = homogeneous-filled permeability
f = weight of gas per unit weight of gas-liquid mixture passing a transverse section of sand column in unit time

Subscripts:

G = gaseous phase
L = liquid phase
0 = inlet end of column
1 = upstream end of transition region
2 = downstream end of transition region
e = critical equilibrium gaseous-phase content of porous medium

Combination terms:

$$a = \frac{c_p W}{KA}$$

$$F = F(P) = \left(\frac{k_L/k}{\mu_L \bar{v}_L} + \frac{k_G/k}{\mu_G \bar{v}_G}\right)$$

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An ANALOG COMPUTER for STUDYING HEAT TRANSFER during a THERMAL RECOVERY PROCESS

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ABSTRACT

A design is presented for an electrical analog computer which can solve non-steady state heat transfer problems in an extensive radial formation containing a moving cylindrical source. The computer is used to simulate a simplified thermal oil recovery process in which heat transfer from a moving, constant temperature source takes place radially by conduction only. Temperature distribution curves are shown for several different assumed modes of travel for the heat source. The data are used to estimate the residual fuel requirements necessary to maintain a self-propagating isothermal front for the particular system being studied.

Although the computer is designed to represent an unique system, conversion factors can be adjusted to show the effects of changing the assumed values of system constants, such as thermal conductivity of the formation and temperature of the source isotherm. Examples are given to illustrate the relative influence the assumed values of these variables will have upon the quantity of fuel required to maintain the source.

The maximum effect of heat transfer by the flowing air stream is estimated mathematically, and shown to be markedly reduced.

Inasmuch as the examples discussed refer to a simplified process, the results are not directly applicable to a practical field operation. It is believed, however, that the data illustrate some general trends which are important in thermal recovery processes.

Data from laboratory and field experimentation can be used to modify the computer to take into account the influence of heat transfer by various mechanisms, for example, by injected air and by fluids ahead of the hot zone. With such refinements it would be possible to estimate more accurately the limiting values for the rate of travel of the high temperature front and for the required air injection rates.

Use of this computer should aid in evaluating the economic feasibility of oil recovery by various thermal processes. It is hoped this paper will stimulate further work by others to help accomplish this objective.

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INTRODUCTION

As the costs of exploration for and development of new oil fields rise, increasing the recovery of oil from established fields becomes more and more important. In fields containing low gravity crude oil, ultimate recoveries by primary means are sometimes less than 10 per cent and often total only 10 to 20 per cent of the oil in place. Conventional secondary recovery methods are not always effective in increasing this total. Methods which have been proposed for increasing the recovery of viscous oils include thermal processes for increasing the mobility of the oil. One method is to provide a moving heat source generated within the formation to heat the oil and a flowing gaseous medium (for example, air) to sweep the oil to the producing wells. The possibility of such a process has intrigued engineers for many years,[1,2,3] but little or no information has been available in the literature relative to the technical or economic feasibility of this method. Recently, however, interest has been revived by publication of laboratory and field test results indicating the feasibility of maintaining

[1]References given at end of paper.

a self propagating heat source in an oil formation. Very high ultimate recoveries were indicated to be possible[4, 5, 6].

To date, numerous laboratory tests have been devoted to studying the many variables involved, such as oil and oil-sand characteristics, pressure, and air flux. Of necessity, such tests are usually made in linear cells. The application of laboratory results to a radial system of sufficient scale to evaluate the economic feasibility of a thermal oil recovery process is extremely expensive and subject to considerable trial and error. One intermediate step is to use mathematical and analog methods to study means of utilizing the experimental information in the most effective manner.

To a large extent, the evaluation of economic feasibility depends upon a knowledge of such factors as sweep-out efficiency, well spacing, and air injection rates and pressures. A study of areal sweep of a combustion pattern has been reported in a recent paper by H. J. Ramey, Jr., and G. W. Nabor.[7]

It is proposed in the present paper to describe a design for an electrical analog computer which can calculate the temperature profile resulting from non-steady state heat transfer from a moving source in an extensive radial system. A method is presented for using such profiles to estimate the fuel required to maintain a moving heat source. The effect of changes in the assumed values of different variables is demonstrated through changes in scale factors in the computer.

In the present study the computer was used to simulate a simplified thermal process in which the single factor of heat transfer by conduction alone was considered. Inasmuch as the nature of the thermal oil recovery process may predetermine the quantity of fuel available for generating the heat source, and the heat transfer characteristics are dependent upon the physical operating conditions, it may be concluded that the optimum mode of travel of the source will be affected by additional factors not included in the present design. Through the utilization of data obtained in laboratory and field experiments, the computer described herein may be modified to evaluate different hypothetical mechanisms for the recovery of oil by thermal means.

APPARATUS AND PROCEDURE

Mathematical or experimental solutions of unsteady state flow problems are often difficult and time consuming. A common method of obtaining a rapid solution to such problems is often found by use of electrical analogs.[8,9,10] One such network[11] has been adapted in our laboratory to study heat conduction from a moving, cylindrical heat source in the earth.

The electrical model makes use of the similarities which exist between the flow of heat in a rigid body and that of charge in a non-inductive electrical circuit.

The method is based on the identity in form between the following electrical and heat flow equations:

Heat Flow	Electrical Flow
$R_t = \frac{\Delta T}{q}$	$R_e = \frac{\Delta V}{I}$
$C_t = \frac{Q_t}{\Delta T_{AVG}}$	$C_e = \frac{Q_e}{\Delta V_{AVG}}$

It follows from this identity in form of the fundamental defining equations that all mathematical results based on them will be similar.

In the analog computer discussed in this paper, the simulated formation was divided into 100 concentric, cylindrical tubes of unit thickness, each varying from the next one by an increment of radius. Because of the symmetry of this two-dimensional problem, it was possible to simplify the electrical network by adjusting the values of the components to represent the thermal capacitance and resistance associated with the radial location of each thermal element. To approximate an infinitely large medium, the last element in the circuit was designed to correspond to a formation volume which was large compared to the entire radial system being studied.

In order that the computer could be operated at a convenient voltage and transient time interval, scale factors were chosen for the conversion from thermal to electrical units, as follows:

I = 0.18 v/°F; that is, 180 v is equivalent to 1000°F.

n = 0.006 sec/hour; that is, one minute in the computer is equivalent to 10,000 hours actual time.

m = 3.04×10^{-10} farads/Btu/°F; that is, one microfarad is equivalent to 3290 Btu/°F.

The following thermal constants were assumed to be representative of a fluid saturated, porous rock:

thermal conductivity, k = 1.6 Btu/sq ft hour °F/ft
specific heat, c = 0.2 Btu/lb °F
density, ρ = 140 lb/cu ft
diffusivity, α = 0.057 sq ft/hour

The scale factors may easily be changed without invalidating the results as long as the relationships between the two systems (electrical and thermal) are maintained. It is possible, within certain practical limits, to study the effect of changing the assumed values of the variables in the thermal systems by making suitable changes in the scale factors. This is important in considering the usefulness of the computer.

For a given position (x) in the thermal system, the thermal resistance is:

$$\Delta R_t = \frac{1}{k A_x/\Delta r_x}$$

$$= 0.625 \frac{\Delta r_x}{A_x} \frac{°\text{F hour}}{\text{Btu}}$$

To convert to electrical units:

$$\Delta R_e = \frac{n}{m} \Delta R_t =$$

$$1.233 \times 10^7 \frac{\Delta r_x}{A_x} \text{ ohms}$$

where A_x is the logarithmic mean area.

For the same element, the thermal capacitance is:

$$\Delta C_t = \pi(r_{x+1}^2 - r_x^2) \cdot 1 \cdot \rho \cdot c$$

$$= 87.6\,(r_{x+1}^2 - r_x^2) \text{ Btu/°F}$$

To convert to electrical units:

$$\Delta C_e = m\Delta C_t =$$

$$2.66 \times 10^{-8}\,(r_{x+1}^2 - r_x^2) \text{ faradays}$$

A schematic diagram of the computer circuit is shown in Fig. 1. The body of the computer, a conventional RC network made of non-inductive resistors and oil-filled condensers, is shown with each of the elements connected to the bars of a large commutator. The voltage source is a 180 v "B" battery, chosen to give full scale deflection of the oscilloscope beam when connected directly to the deflection plates.

To simulate the movement of a heat source, the voltage source is connected to a rotating brush which contacts the commutator bars. A second brush, rotating at a high speed relative to the primary voltage source, is used to transfer the condenser voltage at each element to the oscilloscope plates. By means of an adjustable selector switch synchronized with the source rotor, a triggering signal is sent to a commutator bar adjacent to the last RC element to initiate the oscilloscope sweep. This results in a visual representation of the voltage profile in the computer network for the selected location of the simulated heat source. A photograph of the assembled computer and associated equipment is shown in Fig. 2.

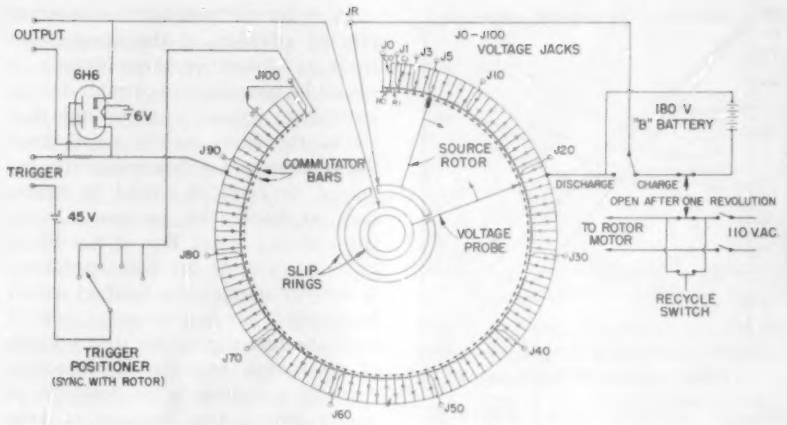

FIG. 1 — SCHEMATIC DIAGRAM OF ANALOG COMPUTER FOR HEAT TRANSFER BY CONDUCTION IN A RADIAL FORMATION.

To operate the computer, the rate of travel of the source rotor is selected by changing the gear ratio on the drive motor. After a suitable warm-up period, the positions of the trigger selector switch are adjusted and synchronization is checked with the oscilloscope sweep circuits. The camera is attached to the oscilloscope and the network voltage profile photographed at the preselected positions.

If the computer is used to simulate a constant temperature source moving through a radial formation, a temperature profile similar to that shown in Fig. 3 is observed on the oscilloscope screen. The vertical distance between grid lines represents a temperature difference of 100°F. The curvature of the grid lines calibrates the beam deflection for the entire screen. The voltage of each segment of the computer network is shown as a spot on the screen at a vertical position corresponding to its numerical value.

This analog computer can be adapted to the solution of heat transfer problems involving steady state or non-steady state conditions and moving or stationary heat sources. In order to check the network design, analog solutions were determined for problems involving a stationary heat source for which the theoretical curves could be obtained by conventional mathematical methods. In general, it was concluded that the network satisfactorily represented a cylindrical system and that the solution of non-steady state problems in a simulated infinite cylindrical medium was feasible for short times. For problems involving long computing times at a given position of the source, the error increases with time.[33] For such problems the accuracy could be improved by using a DC amplifier at each lump in the analog.[12,14,15] However, for problems involving a moving source, the large additional expense involved in such a refinement was not considered necessary.

As described herein, the computer has been designed to study heat conduction problems involving a moving, constant temperature source in a radial formation. It should be pointed out, however, that the general design is applicable to a variety of heat transfer problems involving a moving source. With some modification it would be possible to study non-steady state heat transfer by gases, liquids, and solids, either individually or as an interacting system, in media of different geometrical shapes. In addition, the moving source rotor may be designed to represent a heat source with any of a number of unique properties.

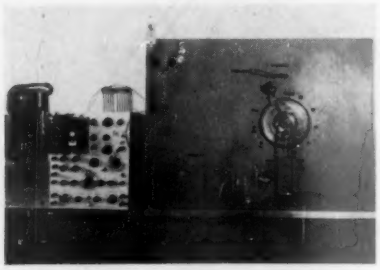

FIG. 2—ASSEMBLED COMPUTER AND ASSOCIATED EQUIPMENT.

ILLUSTRATIVE PROBLEMS

To illustrate the type of problem which can be studied with this computer, several assumed modes of travel of the heat source will be discussed. It should be emphasized that these problems are intended to be illustrative only and are not necessarily representative of a practical field operation.

For the following illustrations, it is assumed that a constant temperature heat source is produced in the formation. Although a number of possible mechanisms for the production of such a heat source may be visualized, for convenience a mechanism similar to that postulated by Kuhn and Koch[4] has been assumed. According to their hypothesis, a combustion zone is produced by burning residual carbonaceous material deposited out of the native crude oil ahead of the high temperature zone. In the idealized case, the temperature of this combustion zone could be maintained at a constant optimum value by adjustment of the rate of air injection into the formation. Although reference will be made throughout the ensuing discussion to the "combustion front" and the associated fuel requirements, any means of obtaining a constant temperature front would result in identical heat transfer characteristics for the particular conditions postulated.

In one set of tests, a constant temperature source was moved radially through the formation at various constant speeds which ranged from 0.874 ft/day to 0.097 ft/day. Temperature profiles were photographed at convenient positions. In Figs. 4, 5, 6, and 7, temperature data from the above tests have been plotted on a semi-log scale to show the computed temperature distributions for different positions of the heat source. It is immediately apparent that (1) at a constant rate of travel, preheating of the formation ahead of the source isotherm increases with distance of travel and (2) at a given radius, preheating increases for slower rates of travel.

These temperature distribution curves may be used to calculate the theoretically required amount of residual fuel to maintain a self-propagat-

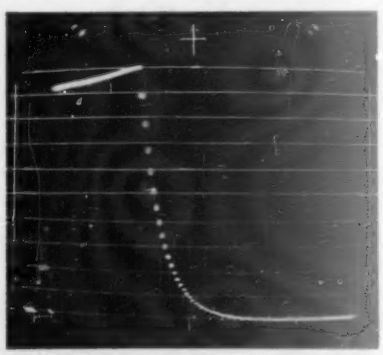

FIG. 3—TYPICAL VOLTAGE PROFILE IN ANALOG COMPUTER NETWORK.

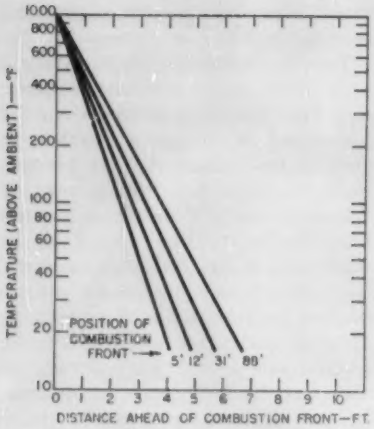

FIG. 4 — TEMPERATURE DISTRIBUTION AHEAD OF COMBUSTION FRONT. **Conduction only in radial formation. Rate of movement of front: 0.874 ft/day.**

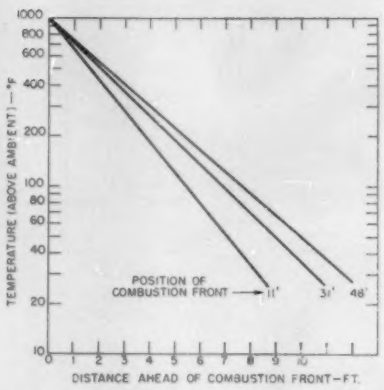

FIG. 5 — TEMPERATURE DISTRIBUTION AHEAD OF COMBUSTION FRONT. **Conduction only in radial formation. Rate of movement of front: 0.353 ft/day.**

ing combustion front at a given rate of advance. In order to make such a calculation, it is necessary to know the instantaneous heat loss from the combustion front. If this heat loss can be supplied by burning the available fuel, the temperature of the combustion front will remain constant and the source will be self-perpetuating as long as sufficient air is supplied. If there is insufficient fuel, the temperature will decrease and, under certain conditions, the process will cease.

The instantaneous heat loss can be determined from the equation, $q = kA\ \partial T/\partial r$. The term, $\partial T/\partial r$, is simply the instantaneous temperature gradient at the heat source and can be readily determined directly from the figures as

$$\partial T/\partial r = \frac{ln\ T_1 - ln\ T_2}{\triangle r\left]\frac{T_2}{T_1}\right.} \cdot T$$

Then the fuel required to maintain the combustion front will be

$$W = \frac{k}{s} \cdot \frac{\partial T/\partial r}{dr/dt} \text{ lb/cu ft of formation}$$

where s is the heat of combustion of the residual fuel (assumed as 17,000 Btu/lb) and dr/dt is the rate of movement of the front in feet per hour.

Through use of the above method, Fig. 8 has been plotted to show the residual fuel required to maintain a moving heat source (temperature = 1,000°F above ambient) in a formation in which heat is transferred radially by conduction alone.

A suitable change in conversion factors ($l = 0.18$, $n = 0.006$, $m = 6.08 \times 10^{-10}$, $r = r_z/\sqrt{2}$), can be made to show the effect of changing the assumed value of the conductivity. In Fig. 9 the fuel requirements to maintain a moving combustion front are indicated for $k = 0.8$, $\triangle T = 1{,}000$.

Similarly, through the choice of a different set of conversion factors ($l = 0.30$, $n = 0.006$, $m = 6.08 \times 10^{-10}$, $r = r_z/\sqrt{2}$), the effect of a change in the temperature of the combustion front can be found. Fig. 10 shows the fuel requirements if $k = 0.8$, $\triangle T = 600$.

In general, Figs. 8, 9, and 10 show that the fuel requirements are higher for the slower rates of travel of the source. Inasmuch as the physical nature of the assumed process makes available only a given amount of fuel, which may be affected by formation and oil characteristics, there should be a minimum rate of advance possible for a self-propagating combustion front. The curves indicate that this critical rate will decrease with distance from the wellbore. This characteristic is a result of the greater preheating by conduction as the combustion front travels away from the wellbore and should be true when the additional effect of injected air is considered.

From the data presented above, it is apparent that the differences between the actual value of k and that used in the computer are not critical in determining the required fuel content, provided k is of the right order of magnitude. Of greater importance in using the data is the value assumed for the temperature at the combustion front, inasmuch as the required fuel content was shown to be directly proportional to the temperature. This indicates one area in which experimental data from laboratory tests would be desirable.

In order to maintain a constant rate of advance of the combustion front as shown in these figures, it would be necessary to provide for an increasing volume rate of injection air as the front travels away from the wellbore. To determine the required air rates, it would be necessary to know the position of the front at any time. This is not likely to be practicable for field operation. A simpler operational method would be to inject air at a constant rate. If both the fuel supply per unit volume of formation and the air injection rate are assumed to be constant, it would appear that because of geometrical factors the minimum rate of movement of the combustion front should be inversely proportional to the radial position.

It is possible to study the feasibility of this mode of operation by either of two methods. In one case, a family of curves, each of which is proportional to 1/radius, can be obtained with a constant rate drive. In the second case, the computer can be set up so that the source rotor can be moved at a rate proportional to 1/radius.

To illustrate the first method, the family of curves in Fig. 8 has been used to examine a mode of travel in which the rate of movement of the combustion front is equal to 8/radius in feet per day. Then for the constant rates of 0.874, 0.353, 0.211 and 0.097 ft/day, the front would be located at approximately 9, 23, 38 and 83 ft, respectively, in order to be traveling at the designated rate. If these points are plotted on Fig. 8 they will all fall at a constant fuel requirement of approximately 2.3 lb/cu ft of formation, indicating that the front would be self-propagating

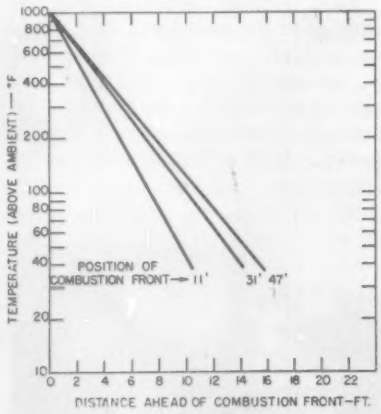

FIG. 6 — TEMPERATURE DISTRIBUTION AHEAD OF COMBUSTION FRONT. **Conduction only in radial formation. Rate of movement of front: 0.211 ft/day.**

under the above conditions.

If the computer is set up so that temperature profiles are obtained at radii, r_1, at the corresponding rate, $8/r_1$, the required residual fuel can be calculated from the computed temperature gradients in the manner described previously. In this case a single curve would be obtained as shown in Fig. 11. Here again the required residual fuel is found to be 2.3 lb/cu ft of formation.

In general, it may be concluded that for this mode of travel the numerical value of both the temperature gradient and the radial velocity of the combustion front must be changing at the same rate. The results indicate also that in the radial system described a constant rate of fuel consumption will result in a constant temperature heat source only if the rate of movement is inversely proportional to the radial position.

In the above discussion, heat transfer by the injected air has been neglected. It is possible, however, to use the available data to estimate the minimum fuel requirements in a system in which no heat is retained behind the combustion zone. This can be done by assuming that all of the heat stored in the rock as the moving source reaches and passes a given radius will be transferred instantaneously by the flowing air stream back to the combustion front. Thus the minimum fuel requirement in such a system can be approximated simply by subtracting the equivalent fuel content of the corresponding volume increment of heated rock from the residual fuel content calculated from the data shown in Figs. 4, 5, 6, and 7. This has been done for a radial thermal system in which $k = 1.6$ and $\triangle T = 1{,}000$ and the calculated

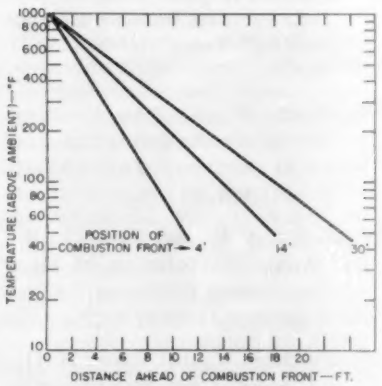

FIG. 7 — TEMPERATURE DISTRIBUTION AHEAD OF COMBUSTION FRONT.
Conduction only in radial formation. Rate of movement of front: 0.097 ft/day.

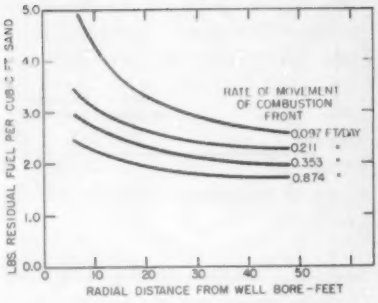

FIG. 8 — FUEL REQUIRED TO MAINTAIN A MOVING COMBUSTION FRONT.
Thermal conductivity: 1.6 Btu/ft² hour °F/ft. Combustion front 1,000°F above Ambient Temperature.

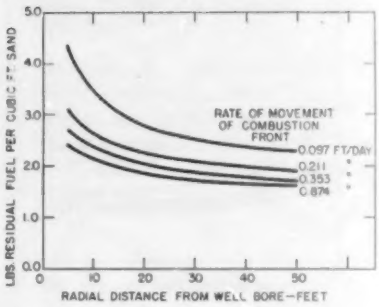

FIG. 9 — FUEL REQUIRED TO MAINTAIN A MOVING COMBUSTION FRONT.
Thermal conductivity: 0.8 Btu/ft² hour °F/ft. Combustion front 1,000°F above Ambient Temperature.

curves have been plotted in Fig. 12. The values for the residual fuel content shown in Figs. 8 and 12 represent two extremes of operation. In the one case (Fig. 8), it is assumed that all of the heat stored in the rock behind the combustion front remains unavailable for raising the temperature of the formation. In the second case (Fig. 12), all of this heat is utilized to the fullest extent.

As a final illustration of the usefulness of the analog, there is shown in Fig. 13 the analog computation of the temperature decay in a radial formation after a heat source has stopped moving. In this problem, the combustion front was moved through the formation at a constant rate of 0.353 ft/day to a radius of 40 ft and then stopped. This might correspond to a system (with heat flow by conduction only) in which air injection has stopped because of equipment failure. From the slow decay of temperature shown, it might be concluded that once a hot zone has been well established, re-ignition of the oil sand following a prolonged shutdown should not be a serious problem.

This problem is similar in nature also to that investigated mathematically by Jenkins and Aronofsky.[10] The temperature increase after 840 days of 70° F at a radius of 100 ft compares reasonably well with their theoretical value of 75° F after two years.

From the above illustrations, it would appear that the computed temperature distribution curves should be useful for studying various factors, such as the best start-up technique and the optimum mode of travel of the heat front. It is obvious, however, that the simplified mechanism set up for the foregoing problems does not simulate closely the heat transfer process existing in a practical field operation. In order to obtain the maximum utility from this machine, it would be desirable to modify it to include additional factors such as heat transfer by the injected air and by the movement of hot fluids ahead of the combustion front. It seems apparent that modification of the computer to study heat transfer by various assumed mechanisms must be coordinated closely with results obtained from laboratory and field experimentation.

CONCLUSIONS

A design has been presented for an electrical analog computer which can solve non-steady state heat conduction problems pertaining to an extensive radial system containing a moving, cylindrical heat source.

It has been the intent of this paper to show the type of problem the analog computer can be adapted to study, and to indicate how its use can be integrated with the results obtained from laboratory data to increase our understanding of possible field applications of oil recovery by thermal methods. A method has been shown for using the temperature distribution curves obtained with the computer to calculate the fuel required to maintain a self-propagating heat source.

Inasmuch as the computer design presented herein takes into account only those heat losses resulting from radial conduction, the data should not be construed as applying directly to field operations. Modification of the computer to include other heat transfer mechanisms depends primarily upon an understanding of the particular thermal oil recovery method being studied. Laboratory scale studies of the thermal process itself aid in determining the most satisfactory mechanism to use.

Because of the complex nature of thermal oil recovery processes, it

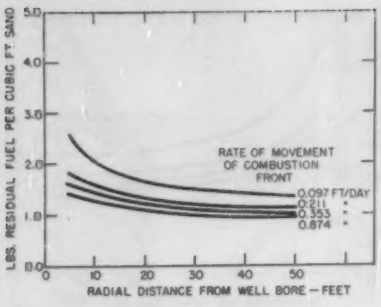
LBS. RESIDUAL FUEL PER CUBIC FT. SAND
RATE OF MOVEMENT OF COMBUSTION FRONT
0.097 FT/DAY
0.211 "
0.353 "
0.874 "
RADIAL DISTANCE FROM WELL BORE — FEET

FIG. 10—FUEL REQUIRED TO MAINTAIN A MOVING COMBUSTION FRONT. **Thermal conductivity: 0.8 Btu/ft² hour °F/ft. Combustion front 600°F above Ambient Temperature.**

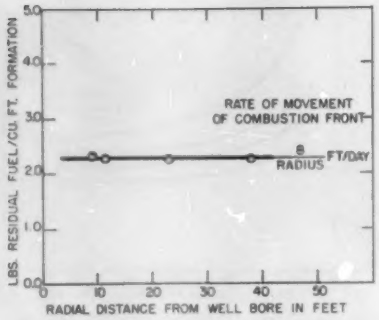
LBS. RESIDUAL FUEL/CU. FT. FORMATION
RATE OF MOVEMENT OF COMBUSTION FRONT
8/RADIUS FT/DAY
RADIAL DISTANCE FROM WELL BORE IN FEET

FIG. 11—FUEL REQUIRED TO MAINTAIN A MOVING COMBUSTION FRONT. **Thermal conductivity: 1.6 Btu/ft² hour °F/ft. Combusion temperature 1,000°F above Ambient.**

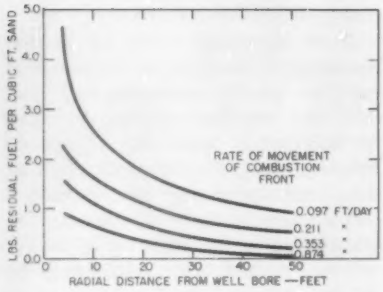
LBS. RESIDUAL FUEL PER CUBIC FT. SAND
RATE OF MOVEMENT OF COMBUSTION FRONT
0.097 FT/DAY
0.211 "
0.353 "
0.879 "
RADIAL DISTANCE FROM WELL BORE — FEET

FIG. 12—MINIMUM FUEL REQUIRED TO MAINTAIN A MOVING COMBUSTION FRONT. **Heat transfer by conduction and no heat stored behind the front. Thermal conductivity: 1.6 Btu/ft² hour °F/ft combustion front 1,000 °F above Ambient temperature.**

would appear that continued efforts of research workers in many different groups will be required to evaluate the numerous possible ramifications in a reasonable time. It is hoped that this paper will stimulate the publication of other work on thermal recovery processes.

ACKNOWLEDGMENT

The authors wish to express their appreciation to the Union Oil Co. of California for permission to publish this paper. We also wish to thank J. E. Sherborne, R. S. Crog, W. S. Pickrell, and R. G. Hawthorne for their constructive discussion of the work.

NOMENCLATURE

Thermal units

R_t = thermal resistance, °F hour/Btu
C_t = thermal capacity, Btu/°F
Q_t = heat stored in C_t, Btu
q = hourly heat flow, Btu/hour
$\triangle T$ = rise in temperature of C_t due to Q_t, °F

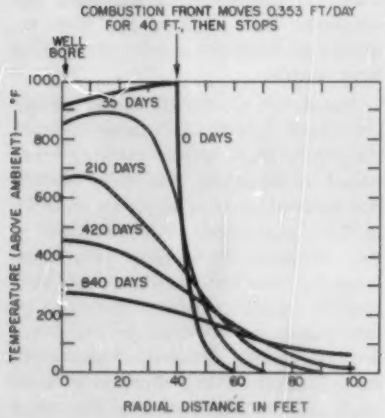

FIG. 13 — CONDUCTION OF HEAT AFTER A COMBUSTION FRONT HAS BEEN STOPPED.

r_t = distance in the thermal circuit (radial), ft
A_n = average cross sectional area of each increment $\triangle r_n$, sq ft
N = number of the element ($\triangle r$) under consideration
t_t = time in the thermal circuit, hour
$\alpha = \frac{k}{c\rho}$ = thermal diffusivity, sq ft/hour
c = heat capacity per unit mass, Btu/lb °F
k = thermal conductivity, Btu/sq ft hour °F/ft
ρ = density of formation, lb/cu ft

Electrical units

R_e = electrical resistance, ohms
C_e = electrical capacity, farads
Q_e = charge stored in C_e, coulombs
I = electrical current, amperes
$\triangle V$ = rise in voltage of C_e due to Q_e, volts
t_e = time in the electrical circuit, seconds
r_e = distance in the electrical circuit (radial), ft

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DISCUSSION

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The authors are to be complimented for their ingenious solution to a problem having an important bearing on future development of thermal oil recovery processes. The interpretation of results from this heat transfer study relative to an in-situ combustion oil recovery process illustrates the utility of this type of theoretical work. Undoubtedly, their electric analog computer will have many other uses in reservoir technology.

With regard to the results of the study, it should be emphasized that for the more conventional well patterns, radial flow conditions exist for only 20 to 30 per cent of the distance from an injection well toward the nearest production well. The results from this study are, therefore, most applicable and important in consideration of the ignition phase of this type of thermal oil recovery process. As the authors implied, the fuel requirements presented are based on assumed thermal properties and an idealized mechanism. Actual fuel consumption can differ greatly from the theoretical values obtained from this study. Nevertheless, the trends illustrated by the authors permit important observations.

For the authors' case of a constant combustion front velocity, the minimum fuel requirement appears especially critical when the burning front is near the injection well and/or when the front is moving at a slow rate. In contrast, the results for the case where the velocity varies inversely with radius of the burning front indicate a fuel requirement that does not vary with position of the burning front. While this result tends to contradict the conclusions drawn from the case of constant velocity, it is believed that most actual operations will fall between these conditions, and the fuel requirement will be substantially higher near the injection well.

During investigation of this thermal recovery process, we computed fuel requirements by an analytical solution of substantially the same heat conduction problem. Two cases were considered: (1) heat conduction from an infinite cylindrical source moving radially in an infinite medium of constant thermal properties, and (2) the same problem with the inclusion of the boundary conditions resulting from consideration of the ignition wellbore.

The solutions to Case (1) for a burning front velocity inversely proportional to the radial position of the front showed the fuel requirement to be entirely independent of position of the front. And for the same thermal conditions assumed by Vogel and Krueger, computed results were in good agreement with the values from the electrical analogy. A fuel requirement of 2.4 lbs/cu ft was obtained as compared with 2.3 reported by Vogel and Krueger. This establishes a direct verification of the electrical analog for a moving source.

A solution for Case (2) at a radial position of 0.5 ft indicated a slightly higher fuel requirement of 2.7 lbs/cu ft. But this is attributed to the effect of the wellbore.

The analytical solutions mentioned above are as follows.

1. Case (1) — Constant velocity of source ($r' = Ut'$).

$$T - T_o = \frac{Uq}{2k}\int_o^t \frac{t'}{(t-t')}\, e^{-\frac{(r^2+U^2t'^2)}{4\alpha(t-t')}}\, I_o\left\{\frac{rUt'}{2\alpha(t-t')}\right\} dt' \quad . \quad . \quad . \quad . \quad (1)$$

Where T_o is the initial temperature, T is the temperature at radius r at time t, q is the rate of heat generation per square foot of frontal area, U is the constant velocity of the burning front, k is the thermal conductivity, t is time, and t' is the time the burning front is located at radius r', α is the thermal diffusivity, and I_o is Bessel's function of the first kind of an imaginary argument. If Equation 1 is integrated for $r = r'$ at t', the fuel requirements may be found from the expression:

$$\frac{\text{lb fuel}}{\text{cubic foot}} = \frac{q}{Us} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where s is the heat of combustion of the fuel.

2. Case (1) — Velocity of source is inversely proportional to the radius ($r'^2 = 2Vt$).

$$T - T_o = \frac{q\sqrt{2V}}{2k}\int_o^t \frac{\sqrt{t'}}{(t-t')}\, e^{-\frac{(r^2+2Vt')}{4\alpha(t-t')}}\, I_o\left\{\frac{\sqrt{\sqrt{2Vt'}}}{2\alpha(t-t')}\right\} dt' \quad . \quad . \quad . \quad . \quad (3)$$

where $V = Ur' = \text{constant}$. . (4)

The fuel requirements may be found by integrating Equation 3 for $r = r'$ at t' and using the expression:

$$\frac{\text{lb fuel}}{\text{cubic foot}} = \frac{qr'}{sV} \quad . \quad . \quad . \quad . \quad (5)$$

3. Case (2) — Wellbore effect included ($r'^2 = 2Vt'$)

$$T - T_o = \frac{qr'}{c\rho V}\int_1^{r'/r_w} \int_o^\infty e^{-\frac{kx^2}{2V}\left(\frac{r'^2}{r_w^2}-1\right)} \times C\left(x, \frac{r}{r_w}\right) C\left(x, \frac{r'}{r_w}\right) \times x\, dx\, d\left(\frac{r}{r_w}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where

$$C\left(x, \frac{r}{r_w}\right) =$$

$$\frac{J_o\left(\frac{xr}{r_w}\right)Y_o(x) - Y_o\left(\frac{xr}{r_w}\right)J_o(x)}{\left\{J_o^2(x) + Y_o^2(x)\right\}^{1/2}} \quad \ldots\ldots\ldots\ldots (7)$$

In Equations 6 and 7, c is the specific heat of the saturated sand, ρ is bulk density, r_w is the radius of the wellbore, J_o and Y_o are Bessel functions of the first and second kind, respectively, of order zero, and x is a variable of integration.

A further refinement of the problem treated by authors Vogel and Krueger is the consideration of vertical heat losses. This would require the expensive modification of rebuilding the RC network in two dimensions, and considering a burning front of finite vertical dimension. Vertical heat loss can be important to the maintenance of self-sustained combustion when the sand section is thin and the well spacing is large. If vertical heat losses were considered, it would also be desirable to account for the lower thermal diffusivity of the "burned" sand section of the reservoir.

We agree with the authors' statement that the data developed by them in this paper should not be construed as applying directly to field operations, inasmuch as the front is known to progress over a range of temperatures, velocities, and fuel consumptions in accordance with incompletely defined rate phenomena occurring in a reservoir. Many challenging problems along these lines remain to be solved.

AUTHORS' REPLY to JENKINS and RAMEY

We should like to thank Rodman Jenkins and H. J. Ramey, Jr., for their pertinent comments. It is gratifying to see the good agreement reported between the analytical and the analog solutions to the problem of determining the fuel requirement in a radial system in which the burning front velocity is inversely proportional to the radial position. This same agreement has been noted by R. G. Hawthorne of our laboratory.

The presentation of the equations used in studying the simplified problems discussed in the paper serves to illustrate the somewhat complicated nature of analytical solutions to heat transfer during thermal oil recovery processes. Equations 3, 6, and 7 illustrate the complexity added to the simple case by considering the wellbore effects. In the computer, wellbore effects are automatically taken care of in the design of the electrical lumps near the wellbore. It would be interesting to see the analytical solutions to the more complex heat transfer problem involving the additional factors of vertical heat losses and heat transfer by the driving gases and condensing fluids.

In general, analytical solutions of this nature are tedious and time consuming unless attacked with modern digital computer techniques. In any case, considerable expense is involved in arriving at numerical answers. It would be of considerable value to the industry to have further work published on solutions to the more complex problems. On the basis of our present thinking, we feel that most such problems can be treated somewhat more simply and inexpensively by the modification of the analog computer.

Jenkins and Ramey have suggested that vertical heat losses be considered as a refinement to the problems treated in the paper. As they have noted, vertical heat losses can be important when considering the problem of maintaining a combustion front in thin oil zones. We believe, however, that the applications in which vertical heat losses are the controlling factor are likely to be the exception rather than the rule. For thicker zones there is some evidence from analytical studies that the effect of vertical heat transfer on fuel requirements is considerably less than the effect of heat transfer by injected air (or inert gases) and possibly by the flowing liquids. The effects of both of these latter factors can be studied rather easily by inexpensive modifications of the analog computer.

As Jenkins and Ramey have emphasized, radial heat flow conditions exist for only 20 to 30 per cent of the distance from the injection well toward the producing well. At the moment, we believe this region to require the most critical consideration when attempting to evaluate the feasibility of starting a successful thermal oil recovery process. However, we feel that a study of heat transfer during later stages of the process can be achieved through relatively simple modifications of the computer. It appears that analytical solutions involving interference between wells might become quite complex.

It is obvious from a consideration of both the comments of Jenkins and Ramey and the authors' reply that there is much to be studied and learned in this field. Both analytical and analog studies can be helpful in solving the many problems involved. However, as mentioned in the paper, their maximum utilization will be achieved through correlation with laboratory and field studies. ★★★

LOCATING CASING SHOE LEAKS with RADIOACTIVE ARGON

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ABSTRACT

Radioactive materials were used underground before the advent of the nuclear reactor. Radium containing ores have been mixed with cements and other materials for later location in oil wells by gamma ray logging since 1940.[1] Perforating bullets have been marked with radium salts, and radioactive materials have been added to drilling muds to find the cause of "lost circulation."[2] More recently colloidal suspensions of radioactive cobalt-60 and silver-110[3] and solutions of I-131[4] have been used in waterflooding operations to determine injection profiles, flow paths and water velocities.

In this paper a recent and interesting underground tracer application is discussed. Development work and field engineering was carried out under the direction of Tracerlab, Inc., with assistance from personnel of the client. A gaseous tracer, argon-41, was used in an attempt to determine the cause of leakage from an underground gas storage reservoir.

STATEMENT OF PROBLEM

This gaseous tracer application was carried out for the Natural Gas Storage Co. of Illinois. This company has developed an underground gas storage field 1,750 ft below the surface of the earth near the village of Herscher, Ill., about 60 miles south of Chicago. The total volume of gas stored in the field was estimated to be about 13 billion cu ft in the spring of 1954. The field has a maximum estimated storage capacity of 90 billion cu ft. The gas is contained in the Galesville sandstone, previously a water bearing formation of about 25 per cent porosity. The water as it is pushed out by the gas forms a barrier for the gas around the edge of the reservoir. Over the top and beneath the bottom of the reservoir are located several layers of impervious rock, which barring cracks or unplugged and unknown wells should act as seals.

Twenty-one injection and withdrawal wells were drilled into the Herscher reservoir and gas injection was begun during the summer of 1953. After a few weeks of gas injection, evidence of gas leakage was detected at the surface; water wells began bubbling and losing prime, and dry spots in the fields indicated gas leakage from uncharted oil wells. In every case, the leakage could not be traced back any further than the water bearing formations a few hundred feet below the surface.

An extensive search was made to locate uncharted oil wells which were believed to be possible channels for the gas from the storage formation to the water containing formation. Long-time residents in the area assisted in the location of several abandoned oil wells. The wells when located were cleaned out and either used as vent wells to relieve the gas pressure in the water formations, or were plugged with cement. None of the wells even approached depths which would endanger the soundness of the storage reservoir.

All of the injection wells were tested for leaks in the casings by conducting neutron surveys and by other techniques.

To detect any leakage up through the cement-filled annulus surrounding the casing, a section of the casing wall in one well was milled out. Then, plugs were installed above and below the cut-out section and pressure applied to the annulus, which proved conclusively that the cement was sound in that well. The well was then plugged with cement and abandoned. In another well, ammonia was injected into the well and a temperature log was made. It was hoped that a leak would be re-

[1]References given at end of paper.
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vealed by a temperature rise resulting from heat being generated by the ammonia passing through the leak and dissolving in formation water.

At the request of the Natural Gas Storage Co. a detailed laboratory study was made by Tracerlab to determine the feasibility of using radioactive gas tracers to locate casing shoe leaks. In the course of the study available references were consulted[5, 6]. Several gaseous tracers were considered, and methyl bromide tagged with bromine-82* was selected as the best available gamma-emitting gaseous tracer. The quantity of tagged methyl bromide tracer required was determined. Techniques for preparation of methyl bromide were worked out**. Then, methods of monitoring water supplies and a method of injection were solved. A schematic diagram of the setup devised to locate casing shoe leaks is illustrated in Fig. 1.

After thoroughly satisfying themselves as to the absence of any hazards to residents of Herscher, or to their own employees, the Natural Gas Storage Co. of Illinois decided to proceed with the tests. Arrangements were made with the U.S. Atomic Energy Commission to obtain the required Br-82. Equipment was shipped to Herscher by Tracerlab for synthesis of the methyl bromide and for monitoring, and a test program was set up.

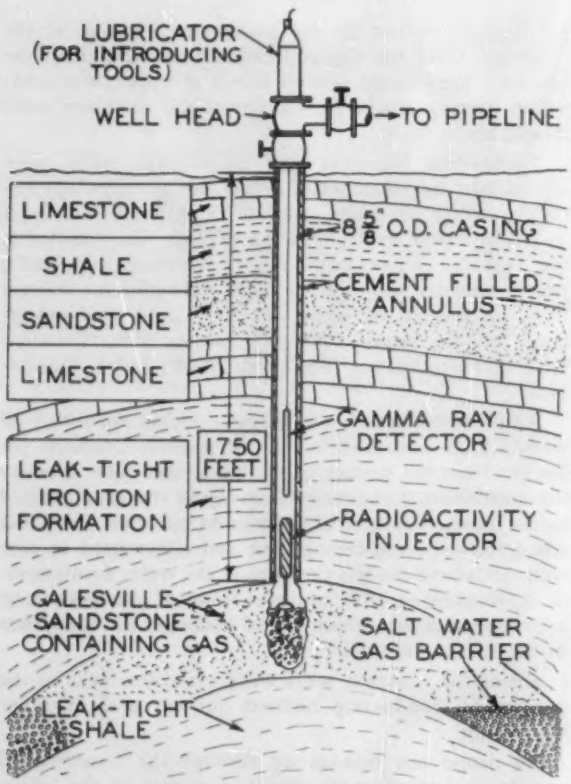

FIG. 1—EQUIPMENT PLACEMENT FOR LOCATING CASING SHOE LEAKS BY RADIOACTIVE TRACER TECHNIQUE.

*Bromine-82 [Br-81 (n, γ) Br-82] .55 to 1.31 MEV γ, .465 MEV β, 35.5 hr half-life.

**The methyl bromide was prepared by reacting KBr, H_2SO_4 and ROH; distilling overhead the methyl bromide, and condensing the methyl bromide in a cold trap maintained at −7°C.

PREPARATION OF EQUIPMENT

Because of its short half-life, argon-41† had not been considered as a tracer for this work. However, L. D. Marinelli of the Radiological Physics Div. of the Argonne National Laboratory, who had been called in as a health physics consultant, suggested that Argonne might be able to prepare this isotope for the tests. Argonne was able to prepare the A-41, approval for this preparation having been obtained from the Isotopes Div., U.S. Atomic Energy Commission. Because of its chemical inertness, low health hazard, and ease of use, A-41 was selected for the tests rather than Br-82. The two-hour half-life of argon-41 dictated that the complete operation, from obtaining the argon-41 from the reactor to its injection into each well, must be carried out on an exacting time schedule.

Irradiation capsules with a 90 cc volume were constructed of aluminum. A chamber for filling the irradiation capsule with stable argon and for removing the radioactive argon was constructed as shown in Fig. 2. The method of filling the capsule was as follows:

The capsule, with the screw cap loose, was placed in the chamber. By manipulation of valves, the chamber and capsule were successively evacuated and then filled with 15 psig of argon four or five times. After the final filling of the capsule with argon the pressure was dropped to atmospheric and the capsule cap tightened. The capsule was checked for leakage by placing it in boiling water and observing if bubbles formed.

The capsule containing the argon was placed in the CP-5 reactor at the Argonne National Laboratories. It was subjected to a flux of 2.3 x 10^{12} thermal neutrons per cm^2/sec for an irradiation time from 12 to 16 hours (overnight), which produced approximately 1,600 mc of argon-41. The reactor was shut down at 8:00 a.m. and the irradiated argon was removed after a 15-minute cooling off period which permitted decay of the 2.4 minute A1-28.

The capsule in a 350-lb lead shield was transported by automobile to the Herscher compressor station. The radioactive argon was transferred to the injector (Fig. 3) in a hood by placing the irradiation capsule (after removing the screw cap with a long handled tool) into the chamber which was used for filling the capsule. The injection tank, having previously been evacuated, was connected to the chamber through a manifold as shown in Fig. 2. Four in. of lead shielding were placed around both the chamber and injection tank. By opening the injection tank valve, the radioactive argon was drawn into the tank until the pressure equalized. The tank valve was then closed and the chamber pressured to 15 psig with stable argon gas. These operations were repeated until a survey meter located near the injection tank ceased to indicate an increase in radiation. The

TABLE 1 — TYPICAL SCHEDULE WITH RADIOACTIVITY VALUES FOR EACH OPERATION

Operation	Time	Quantity of A-41 Present
Remove argon-41 from reactor	8:15 am	1470 mc
Injector and Detector in Position	12:00 pm (noon)	356 mc
Injection timer opens valve to release tracer	12:30 pm	286 mc
Injection timer closes valve	12:40 pm	(186 mc injected)
Test conclusion — Withdraw injector	5:30 pm	43 mc total (27 mc injected 16 mc in tank)
24 hours after injection	12:40 pm (next day)	.0147 mc total .0093 mc injected .0054 mc in tank

†Argon-41 [A-40 (n, γ) A-41] 1.37 MEV γ, 109 minute half-life.

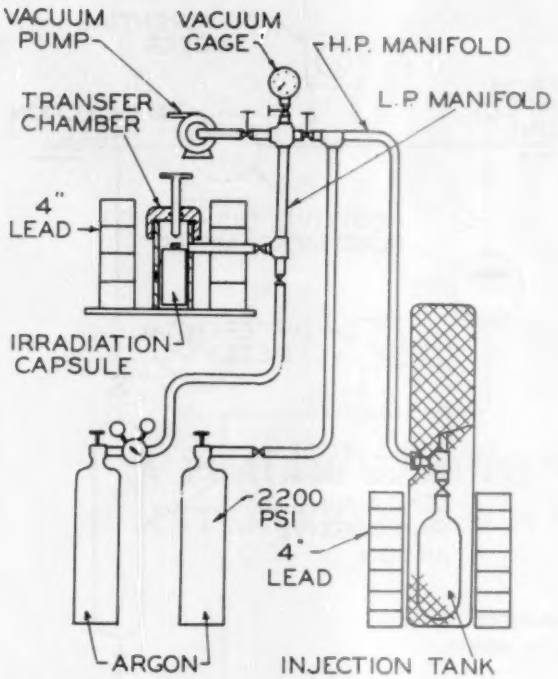

FIG. 2 — LABORATORY SETUP FOR TRANSFER OF RADIOACTIVE A-41 TO GAS INJECTOR.

injection tank was then pressurized with stable argon to 2,000 psig. At the time of transfer, the activity of the empty capsule was estimated to be over 1 curie due to the impurities in the aluminum (principally copper-64, 12.88 hour half-life), even though the purest available commercial aluminum was used for capsule fabrication.

TEST PROCEDURE

The injection apparatus shown in Fig. 3 comprised a 12.3 cu ft, 2,000 psi tank, a pressure regulator which determined the injection flow rate, and a timing mechanism which opened and closed the release valve at predetermined times.

The base of the well had been enlarged to present more formation area to the injection gas, as shown in Fig. 1. This space was packed with gravel to conserve the radioactive gas and support the injector. The injector, containing the radioactive gas, was lowered to the base of the casing shoe in the injection well by use of a shooters hook. At the bottom of the well, the shooters hook was released from the injection apparatus and withdrawn from the well. A gamma ray detector (3-in. diameter by 3-ft long high-pressure ionization chamber) was lowered into the well and set at the elevation where the indicated radiation level was about one-third to one-half scale due to direct radiation from the injection tank (approximately 12 ft above the injector). The arrangement of the detector and injection apparatus within the well is shown in Fig. 1. The gas flow into the well was regulated to restrain the radioactive gas, when injected, from flowing upwards in the well.

At the time of injection, the radiation level at the detector decreased, indicating that the radioactive gas was moved from the injection tank down to the base of the well. Since the well pressure was approximately 700 psig and the tank pressure was 2,000 psig, only two-thirds of the radioactive gas could be injected.

A typical schedule with radioactivity values for each operation is given in Table 1.

The radiation level approximately 12 ft above the casing shoe was recorded for a minimum of four hours after injection. At 30 minutes and at 60 minutes after injection, the radioactive gas was brought up to the detector by venting gas from the well through a positive displacement meter. As soon as the radiation level at the detector indicated that the radioactive gas was up to the detector, a sufficient amount of gas was metered into the well to move the radioactive gas back to the bottom of the casing shoe.

It was found that very small gas leaks in the well casing or out the top of the wellhead could be quantitatively measured by timing the uphole movement of the radioactive gas. In several instances (with all known gas inlet valves closed) the radioactive gas was found to move down in the well. This indicated a down hole flow in the well, caused by leakage through the valve used to isolate the injection well from the gas injection line.

Three hours after injection of the tracer, the radioactive gas was drawn 150 ft up the casing by venting gas from the well. A volume of gas twice the quantity of the vented gas was then injected into the well. This procedure was followed to assure that the volume of radioactive gas was sufficiently large to fill the cavity at the base of the well and to increase the probability of the tracer moving up any shoe leak. At the time of

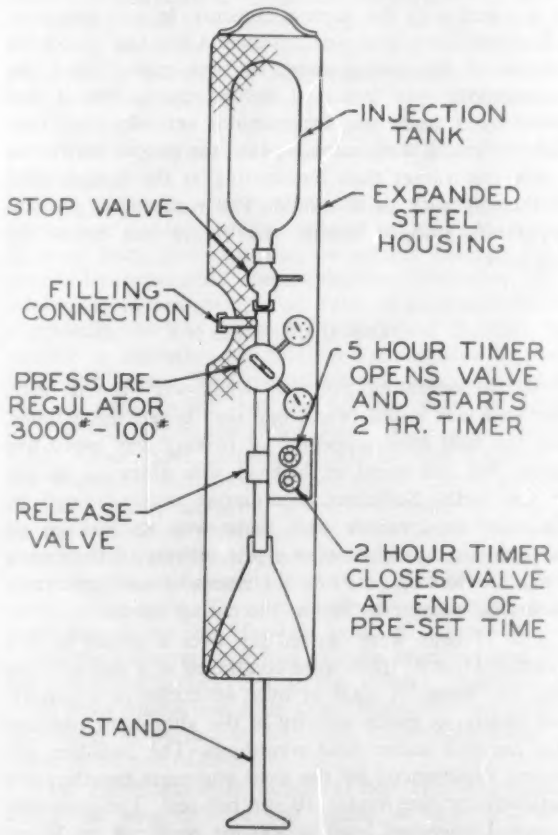

FIG. 3 — RADIOACTIVE GAS INJECTOR.

venting the gas, about 30 mc of released A-41 remained in the well. This amount was sufficient to give a reading more than seven times full scale when the gas flowed past the detector.

At the conclusion of each test, a complete gamma ray log was made of the well. This log was compared with a background log made before the radioactivity testing program in order to check for new radiation abnormalities.

Even though the radioactive gas was mixed with 150 linear ft of casing gas, some question still existed as to whether the volume of radioactive gas was sufficient in size to assure that some of the tracer would reach any leak. To dispel this doubt several wells were tested by mixing the radioactive argon with 500 linear ft of casing gas, and in other wells the radioactive gas was mixed with a full length of casing gas, 1,750 ft or approximately 600 cu ft at 700 psi for the 8-in casing.

To assure a relatively even mixture of gas throughout these large volumes, a controlled mixing system was devised. The radioactive argon was injected at the top of the well by using a purge bottle in place of the injector. A metering arrangement as shown in Fig. 4 permitted regulating the ratio of radioactive gas to natural gas. An added advantage of this method of introduction was that a larger percentage of the radioactive argon could be injected into the well.

Prior to injecting the radioactive argon into the well the gamma ray detector was lowered to a level 5 ft above the casing shoe. The radiation level at the detector was above full scale throughout the passage of the full casing length of gas.

In the tests where the down-hole injector was not used, it was possible to log completely to the bottom of the well with the gamma detector. In two instances, a high radiation level was observed a few feet above the bottom of the casing shoe. In both cases where the radioactivity was indicated behind the casing it was noted by a study of core samples and elevation data that the casing shoe extended into the porous formation a few feet rather than terminating at the bottom edge of the cap rock as it should. The radioactive gas was apparently trapped behind the casing just below the cap rock.

CONCLUSIONS

All 20 operating injection wells were tested once; one well was tested twice; one well tested three times, and the well most suspected of leaking was tested five times. No indication of leakage was observed in any of the wells. Sufficient information was obtained by the tests to conclude that there was no leakage up through the casing annulus in the vicinity of the casing shoe. The loss of gas from the reservoir was apparently occurring elsewhere than at the casing shoes.

The 27 tests were carried out over a period of 3½ months. Most of them were conducted at a rate of three tests per week. A total of over 40 curies of argon-41, and nearly as much activity in the aluminum capsules was handled under field conditions. The radiation exposure experienced by the field engineers handling the radioactivity was under 10 mr per test. The presently accepted tolerance level is 300 mr per week or 50 mr per day.

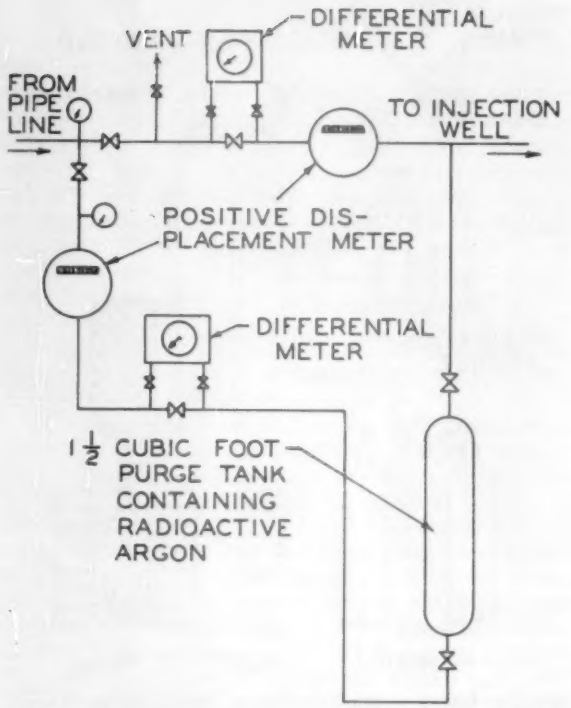

FIG. 4—METERING MANIFOLD FOR MIXING A-41 WITH NATURAL GAS.

ACKNOWLEDGMENT

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The authors also wish to thank the Natural Gas Storage Co. of Illinois for their permission to publish this information, and the personnel of that company for their great help in conducting the field leakage tests.

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A PRACTICAL METHOD for TREATING OILFIELD INTERFERENCE in WATER-DRIVE RESERVOIRS

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ABSTRACT

A practical analytical method is developed in this paper which provides the practicing reservoir engineer with a handy method for analyzing oilfield interference problems. The procedure employed entails the principle of superposition of individual effects. A set of charts has been developed and can be used to evaluate the individual effects. The charts represent non-steady state pressure distribution in an extensive aquifer due to a constant rate of production from an oilfield which can be approximated by circular geometry; they are constructed from solutions to the diffusivity equation considering a circular sink as distinguished from a point sink. The solutions are obtained partially from mathematical considerations and partially from analog and digital computations.

By virtue of the method of images, the charts can be used also to treat the case of production near a fault. In addition, provisions are made for treating oil fields, which are produced by partial water-drive.

Treating an actual field case is deferred to a subsequent writing; however, illustrative example is presented to demonstrate the method of application.

The pressure distribution in linear and limited radial aquifers is currently under study.

INTRODUCTION

With the increasing difficulty of discovering new oil reserves, attention is necessarily focused on the efficient development and production of existing reservoirs. Efficient production depends on the availability of reliable means for predicting the pressure-production behavior of oil fields. The prediction is usually performed by analytical methods or computers. Analytical methods are often limited to systems which can be approximated by simple geometry. However, analytical methods have the distinct advantage of being readily performed without special equipment. Analog and digital computers lend themselves to a variety of problems, but are not always locally available and consequently their use is limited.

One particular situation in which analytical techniques are needed involves studies of multiple, water-drive oil fields sharing a common aquifer. Such oil fields are in hydrodynamic communication. Therefore, production from any of the oil fields is accompanied by a pressure decline which is transmitted through the aquifer to the other oil fields and manifested as pressure interference. The rate of propagation of the pressure decline is such that the pressure may be significantly reduced many miles away from a producing pool. An example of pressure interference is found in the Woodbine formation in East Texas. There, a dozen or more pools, including several of major size, draw on the Woodbine formation for water drive. The pressure in the water-bearing portion of the formation has been significantly reduced over an area of several thousand square miles. This reduction of pressure has been such that when the Hawkins pool was discovered in 1940, the pressure in it had already been reduced 280 psi below the initial value in the aquifer. This resulted from prior production from other Woodbine sand pools, including, in particular, the East Texas field some 20 miles to the east of Hawkins.[1]

The above example indicates that the interference effect can be significant and should be taken into con-

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[1]References given at end of paper.

sideration in predicting the pressure-production behavior of oil fields in a common aquifer. This problem is becoming more important because of the increasing frequency of its occurrence. In addition, it usually concerns more than one operator, in which case unitization may be deemed desirable.

Analog computers have been used successfully to treat this type of problem[3,5], but such computers are not always available to practicing reservoir engineers. In view of this, a practical analytical method has been developed and is presented in this paper. It provides the practicing reservoir engineer with a handy tool for analyzing oilfield interference problems.

PRELIMINARY CONSIDERATIONS

Superposition Theorem

The procedure employed to treat oil fields in interference entails the principle of superposition. Mathematically, the superposition theorem[4,5] states that the linear combination of particular solutions to a linear and homogeneous differential equation is a solution to the differential equation. The superposition theorem is a useful tool for treating systems upon which involved boundary conditions are imposed. The general solution is the summation of the particular solutions obtained by treating one boundary condition at a time.

The transient flow of compressible liquid in a uniform porous matrix is described by the diffusivity equation, which is linear and homogeneous and therefore is subject to superposition. It follows, that the performance of multiple oil fields in a common aquifer can be evaluated from the separate solutions obtained by dealing with one field at a time. In essence, if the pressure change associated with producing each and every field were computed individually (i.e. ignoring the presence of all oil fields but one) for a time instant, t, and at some arbitrary point in the reservoir system, then the total pressure change at this point and time instant is given by the sum of all individual changes. For that matter, the arbitrary point may well be the effective center or any other appropriate point in an oil field, and the time instant may represent some assigned future date at which it is desired to predict the behavior of the system.

For illustration, assume two oil fields, A and B, located in a common aquifer. Producing oil field A is accompanied by a pressure change in A and a relatively smaller pressure change in B. Similarly, producing oil field B is accompanied by simultaneous pressure changes in B and A.

Let P_{Aa} = pressure change in A due to A's production,
P_{Ab} = pressure change in A due to B's production,
and define similarly P_{Bb} and P_{Ba}. Then the total pressure change in A,

$$P_A = P_{Aa} + P_{Ab}$$

and the total pressure change in B,

$$P_B = P_{Bb} + P_{Ba}.$$

P_{Ab}, P_{Ba}, and similar terms will be labeled hereafter "interference pressure change," as distinguished from P_{Aa}, P_{Bb}, and similar terms which represent the pressure change in an oil field due to its own production.

The pressure change terms depend on the rates of production and the physical characteristics of the reservoir system. The case of an extensive aquifer is treated by solving the diffusivity equation. The solution represents the pressure distribution in the reservoir system and permits the evaluation of the individual changes.

Method of Images

The aquifer mentioned earlier was assumed extensive. As a modification, it is proposed to consider the case of an oil field located in an extensive aquifer, one side of which is limited by a straight extensive fault. In this case the benefit derived by the oil field from the aquifer is curtailed by the presence of the fault, and the resulting effect can be expressed as pressure interference. This situation is usually referred to as production near a fault[6] and is treated as a special case of oilfield interference by applying the method of images.[7]

A fault is defined here as a boundary perpendicular to which no flow will take place. This fact can be represented analytically by placing a mirror image of the oil field in offset position and assuming the image to be produced in a manner identical to the oil field. The mirror image represents a fictitious oil field which is placed symmetrically with respect to the fault. This procedure reduces the component of flow perpendicular to the line of symmetry to zero and therefore fulfills the boundary condition required by the fault. The problem is thus transformed to a simple case of interference between two identical oil fields located in an extensive aquifer. The pressure change observed at the oil field will be the sum of the effects of the oil field and its image. Evidently, the effect of the image will be small in the early life of the oil field and will grow larger with time, depending on the distance between the oil field and the fault.

ASSUMPTIONS AND LIMITATIONS

Before proceeding to the solutions of the diffusivity equation, it would be advisable to review some characteristics of reservoir systems to be treated in the following sections of this paper. The reservoir system is assumed to consist of an extensive aquifer in which a number of oil fields are located. It is subject to the following definitions, assumptions, and limitations.

Aquifer Characteristics

1. An extensive aquifer is defined as an aquifer, the exterior boundary of which is sufficiently removed from the oil fields that it does not influence their performance during the period of analysis. For all practical purposes, this assumption is valid for an aquifer having a size about 600 times that of the largest oil field[8] in the reservoir system.

2. In applying the method of images to treat the problem of production near a fault, the aquifer is assumed extensive and bounded by a straight fault. This aquifer is represented geometrically by an infinite half plane and the assumption is justified on condition that the size of the aquifer is about 300 times that of the oil field and the length of the fault is about 25 times the field's effective diameter.

3. The compressibility coefficient, which is defined as the sum of the water and the rock effective compressibilities, is assumed constant and independent of the pressure. Note that while in the following analysis only the expansion due to the water compressibility is taken into account explicitly, superposed effects due to the compressibility of the rock, which may be appreciable, readily fall within the scope of the analysis. For it may be shown[9] that if the porous medium, as well as

the entrained fluid, be considered as compressible, the diffusivity equation remains unchanged, except that the compressibility coefficient is to be considered as the sum outlined above.

4. The porous matrix is isotropic and uniform with respect to permeability, porosity, and thickness.

5. All flow through the aquifer is macroscopically laminar, two-dimentional, and in a horizontal plane. Thus, the flow is governed by Darcy's law and the effects of gravity are neglected.

Oilfield Characteristics

1. Each oil field is considered as a "ring" of production with influx equal to the water influx into the field and with pressure equal to the pressure at the original oil-water interface. A "ring" of production is used to imply a circular sink, as distinguished from a point sink, and represents an oil field the areal configuration of which can be approximated by a circle. Note that radial flow obtains when the effect of each field is considered individually.

2. The rate of water influx is equal to the production rate, provided that the expansion of the oilfield fluids and rock resulting from pressure changes is negligible. If this assumption were not justified, reliable predictions could be achieved by employing an iterative scheme as shown in a following section.

3. The interference pressure drop computed at the effective center of an oil field represents the areal average pressure drop, if the oilfield radius were small, and/or the distance between the oil fields were large. If neither condition were satisfied, the interference pressure drop should be calculated for more than one location in the oil field. The number of locations depends on the desired degree of accuracy.

The above assumptions should not imply that actual oil fields are strictly circular and that aquifers possess isotropy and uniformity. However, these assumptions provide a convenient approximation for many actual systems. The ensuing results, as evidenced by past experience, will give good estimates even when applied to systems that deviate considerably.

SOLUTIONS OF DIFFUSIVITY EQUATION

The individual components required to evaluate the total pressure change are obtained from solutions of the diffusivity equation considering one ring of production. The diffusivity equation describes non-steady state flow of a compressible liquid in uniform porous media and is derived[10] by combining Darcy's law with the continuity equation. By dealing with one ring of production at a time, radial flow obtains and the diffusivity equation takes the form

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{f\mu C_w}{k}\frac{\partial p}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f, k, μ and C_w represent porosity, permeability, water viscosity and compressibility, respectively. The term $\frac{f\mu C_w}{k}$* represents the diffusivity of the aquifer and is advantageously eliminated by introducing dimensionless time, $\underline{t}$, pressure change, $\underline{P}(\underline{r}, \underline{t})$ and radius, $\underline{r}$, such that,

$$\underline{t} = kt/f\mu C_w r_w^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\underline{P}(\underline{r}, \underline{t}) = 2\pi khP(r, t)/\mu q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3),$$

and $$\underline{r} = r/r_w \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4),$$

where r_w is the radius of the ring of production and represents the effective radius of the oil field. Equation 1 then becomes

$$\frac{\partial^2 \underline{P}}{\partial \underline{r}^2} + \frac{1}{\underline{r}}\frac{\partial \underline{P}}{\partial \underline{r}} = \frac{\partial \underline{P}}{\partial \underline{t}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The pressure change in an oil field due to its own production (P_{Aa}, P_{Bb}, . . . etc.) is obtained by solving Equation 5 for $\underline{r} = 1$ and has been treated by Van Everdingen and Hurst.[11] The interference pressure change (P_{Ab}, P_{Ba}, . . . etc.) in an oil field due to producing an adjacent oil field is obtained by solving Equation 5 for $\underline{r}$ equal to the dimensionless distance between the centers of oil fields.

The solution of Equation 5, for all practical values of $\underline{r}$ and $\underline{t}$, is developed in this paper for the constant rate case and the following boundary conditions: (1) $\underline{P}(\underline{r}, 0) = 0$ indicating uniform initial pressure over the entire aquifer; (2) $\underline{P}(\underline{r}, \underline{t}) \to 0$ as $\underline{r} \to \infty$, indicating an extensive aquifer; and (3) $\left(\frac{\partial \underline{P}}{\partial \underline{r}}\right)_{\underline{r}=1} = -1$, indicating a constant volume rate of water influx of $2\pi k/\mu$ per unit thickness.

This solution represents the pressure distribution, $\underline{P}(\underline{r}, \underline{t})$, in an extensive aquifer due to a ring of constant production. Once $\underline{P}(\underline{r}, \underline{t})$ is obtained for a constant rate of production, it can be easily computed for any rate which may vary with time. Again, this is accomplished by the superposition theorem. It will be demonstrated in the following section of this paper.

The above-mentioned solution is treated explicitly in the Appendix. The solution is obtained partially from mathematical considerations employing the Laplace transform and the concept of a continuous point sink and partially from analog and digital computations. The former provide accurate expressions of $\underline{P}(\underline{r}, \underline{t})$ for $10^{-2} > \underline{t} > 500$. However, in treating oil fields (in which case r_w can have a large numerical value) the value of $\underline{t}$ can be easily less than 500 even for large values of absolute time, t. Therefore, analog and digital computers were used to bridge the gap between $\underline{t} = .01$ and 500.

Analog computation was performed by the use of a resistance-capacitance type analyzer. Digital computation was accomplished by translating the diffusivity equation into a set of difference equations which were solved simultaneously with the aid of a digital computing machine called "Datatron." The digital computation provided values of $\underline{P}(\underline{r}, \underline{t})$ which are accurate to three decimal places. This is adequate accuracy considering the degree of uncertainty associated with most properties of reservoir systems.

The solution of the diffusivity equation for the constant pressure case was treated by Andrew Gemant[12], for the following boundary conditions: (1) $\underline{P}(\underline{r}, 0) = 0$, indicating uniform initial pressure over the entire aquifer; (2) $\underline{P}(\underline{r}, \underline{t}) \to 0$ as $\underline{r} \to \infty$, indicating an extensive aquifer; and (3) $\underline{P}(1, \underline{t}) = 1$, indicating constant unit pressure drop at $\underline{r} = 1$.

The rate of water influx asociated with this set of

*See Letter Symbols for Reservoir Engineering, *J. Pet. Tech.*, Jan., 1955, 38. Symbols not included in above mentioned list are explained in Nomenclature.

boundary conditions was discussed in detail by Carslaw and Jaeger[7], and Van Everdingen and Hurst.[11]

PRACTICAL CONSIDERATIONS

Values of the dimensionless pressure change, $\underline{P}(\underline{r}, \underline{t})$, for unit rate of water influx are presented in graphical form. Figs. 1 to 3 cover the ranges of $\underline{t}$ from 10^{-3} to 10^{3} and $\underline{r}$ from 1 to 64. These include essentially all ranges of $\underline{r}$ and $\underline{t}$ encountered in practice. Values of $\underline{P}(\underline{r}, \underline{t})$ for $10^{-3} > \underline{t} > 10^{3}$ and $\underline{r} > 64$ can be accurately calculated from Equation 9 of the Appendix. The charts are readily used to evaluate the pressure drop at any point in an extensive aquifer due to some prescribed rate of oil production.* Presenting the charts in dimensionless form permits the evaluation of the pressure drop for any reservoir system independent of its physical characteristics, but within the limitations outlined earlier.

If at zero-time the rate of production of an oil field A, of radius r_{wa}, were some value q_A then the pressure drop at its boundary over a period of time t is given by the relation,

$$P_{Aa}(t) = P(r_{wa}, t) = 887.6 \frac{\mu}{2\pi kh} (q_A)\, \underline{P}(1, \underline{t}),$$

and the interference pressure drop in an adjacent oil field B is given by,

$$P_{Ba}(t) = P(\underline{r}_A r_{wa}, t) = 887.6 \frac{\mu}{2\pi kh} (q_A)\, \underline{P}(\underline{r}_A, \underline{t}).$$

Where $\underline{t}$ is the dimensionless equivalent of t,

$$\underline{t} = (4.56)\ (10^{-1}) \frac{kt}{f\mu C_w a},$$

and $\underline{r}_A$ is the distance between the centers of A and B in multiples of r_{wa}. The variables in these and the following equations are expressed in units common to oilfield usage. Thus,

P = pressure change in psi,
μ = viscosity in cp,
C_w** = water compressibility vol/vol/psi,
q = production rate in reservoir B/D,
k = permeability in md,
h = thickness in ft,
t = time in days,
f = porosity, fraction, and
A = oilfield area in acres.

Furthermore, if during the period of interest, t_n, the production rate of A varies, then the pressure drop in

*For water-drive reservoirs the rate of oil production is equal to the rate of water influx plus the rate of expansion of hydrocarbon content. The rates of oil production and water influx will be used interchangeably hereafter, since one is easily converted to the other.

**In case the rock compressibility is appreciable, C_w should represent the sum of the water and rock effective compressibilities.

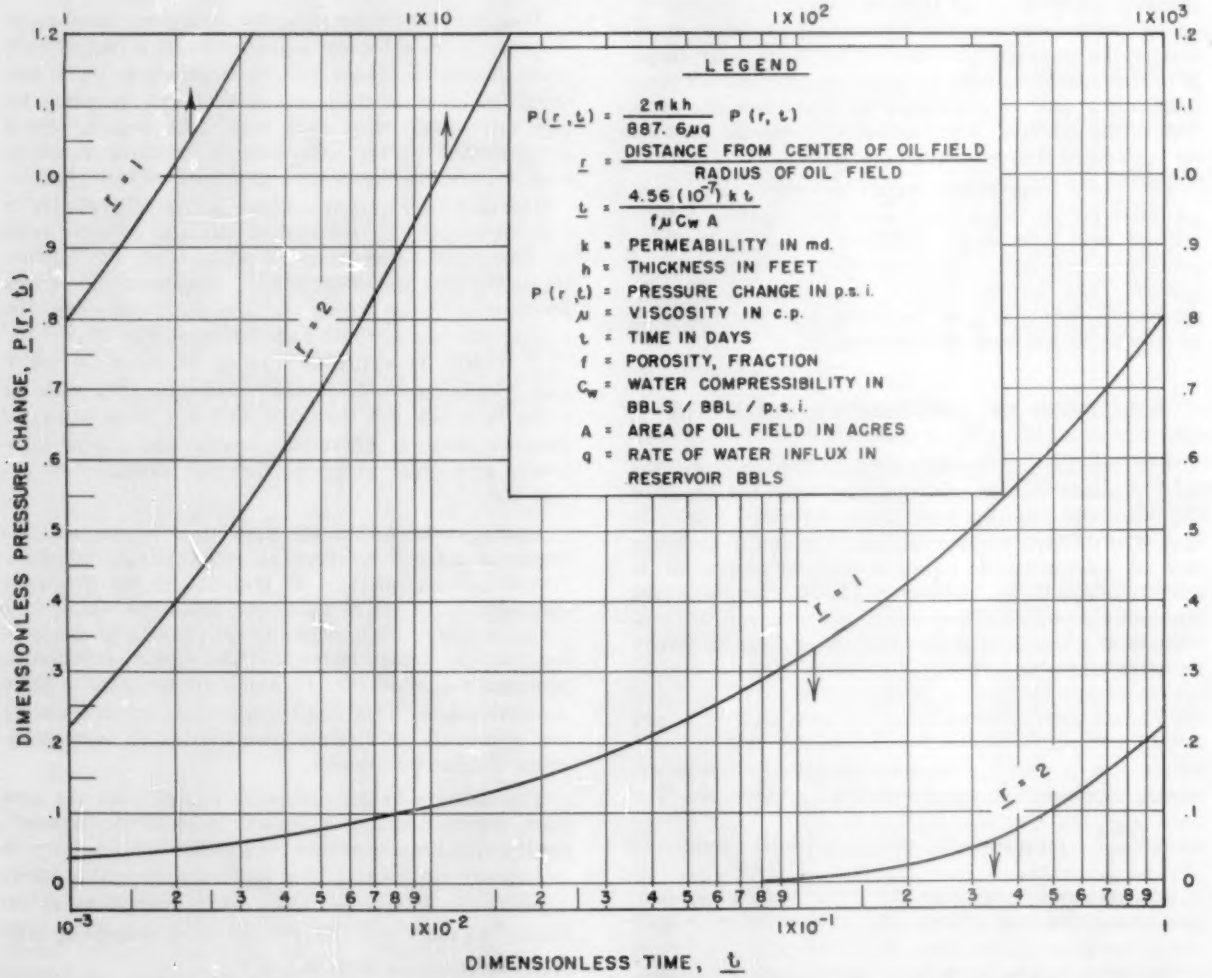
1 X 10
1 X 10²
1 X 10³
LEGEND
P(r, t) = 2πkh / 887.6μq P (r, t)
r = DISTANCE FROM CENTER OF OIL FIELD / RADIUS OF OIL FIELD
t = 4.56 (10⁻⁷) k t / fμ Cw A
k = PERMEABILITY IN md.
h = THICKNESS IN FEET
P (r, t) = PRESSURE CHANGE IN p.s.i.
μ = VISCOSITY IN c.p.
t = TIME IN DAYS
f = POROSITY, FRACTION
Cw = WATER COMPRESSIBILITY IN BBLS / BBL / p.s.i.
A = AREA OF OIL FIELD IN ACRES
q = RATE OF WATER INFLUX IN RESERVOIR BBLS
r = 1
r = 2
r = 1
r = 2
DIMENSIONLESS PRESSURE CHANGE, P(r, t)
DIMENSIONLESS TIME, t
10⁻³
1X10⁻²
1X10⁻¹
1

FIG. 1—PRESSURE DISTRIBUTION—INFINITE RADIAL SYSTEM—CONSTANT RATE CASE.

psi at any point in the aquifer is given approximately by the sum

$$P(r, t_n) =$$

$$887.6 \frac{\mu}{2\pi kh} \sum_{i=0}^{n-1} \left[q_A(t_{i+1}) - q_A(t_i) \right] P(r, t_n - t_i) \quad . \quad (6)$$

where t_i represents time instants ($t_0, t_1, t_2 \ldots t_n$) and $q_A(t_i)$ represents average production rate during the time interval t_{i-1} to t_i.

Inserting the proper values of r and the corresponding values of $P(r, t)$ in Equation 6, gives the pressure drop in A and the interference pressure drop in B due to production from A. The same approach is employed to yield the effects of production from B, thus obtaining the total pressure drop in A and that in B. This procedure is used to predict the pressure behavior of two oil fields in a common aquifer for preassigned production schedules.

Let it be required to predict the pressure-production behavior of oil fields A and B if A's production and B's pressure were preassigned and denoted by $q_A(t)$ and $P_B(t)$, respectively. The procedure in this case consists of evaluating the pressure drop in A and that in B due to $q_A(t)$ by using Equation 6 as pointed out earlier. The pressure drop at B, $P_{Bb}(t)$, due to its production, is determined next and equals the preassigned pressure drop, $P_B(t)$, less the pressure drop at B due to $q_A(t)$. Once $P_{Bb}(t)$ is determined as a function of time, the cumulative production from B is predicted from the following equation:

$$Q_B(t_n) =$$

$$15516\, fC_w Ah \sum_{i=0}^{n-1} \left[P_{Bb}(t_{i+1}) - P_{Bb}(t_i) \right] Q(t_n - t_i)$$

. . . . . (7)

The variables in this equation are expressed in units common to oilfield usage and Q is dimensionless water-influx term for unit pressure drop at $r = 1$. The application of Equation 7 was illustrated by A. T. Chatas[12] with the aid of Van Everdingen and Hurst's[11] constant pressure solution. The rate of production from B, $q_B(t)$, it then used to evaluate $P_{Ab}(t)$ by employing Equation 6. The sum of $P_{Aa}(t)$ and $P_{Ab}(t)$ gives the total pressure drop in A.

Another combination arises if the pressure drop in both A and B were preassigned and denoted by $P_A(t)$ and $P_B(t)$ respectively. To predict the rate of production of each field, it is necessary to resolve the total pressure drop in each into the components, $P_{Aa}(t)$, $P_{Ab}(t)$, $P_{Ba}(t)$ and $P_{Bb}(t)$, which are related by the following four algebraic equations:

$$P_B(t_n) = P_{Ba}(t_n) + P_{Bb}(t_n) \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$P_A(t_n) = P_{Aa}(t_n) + P_{Ab}(t_n) \quad . \quad . \quad . \quad . \quad . \quad (9)$$

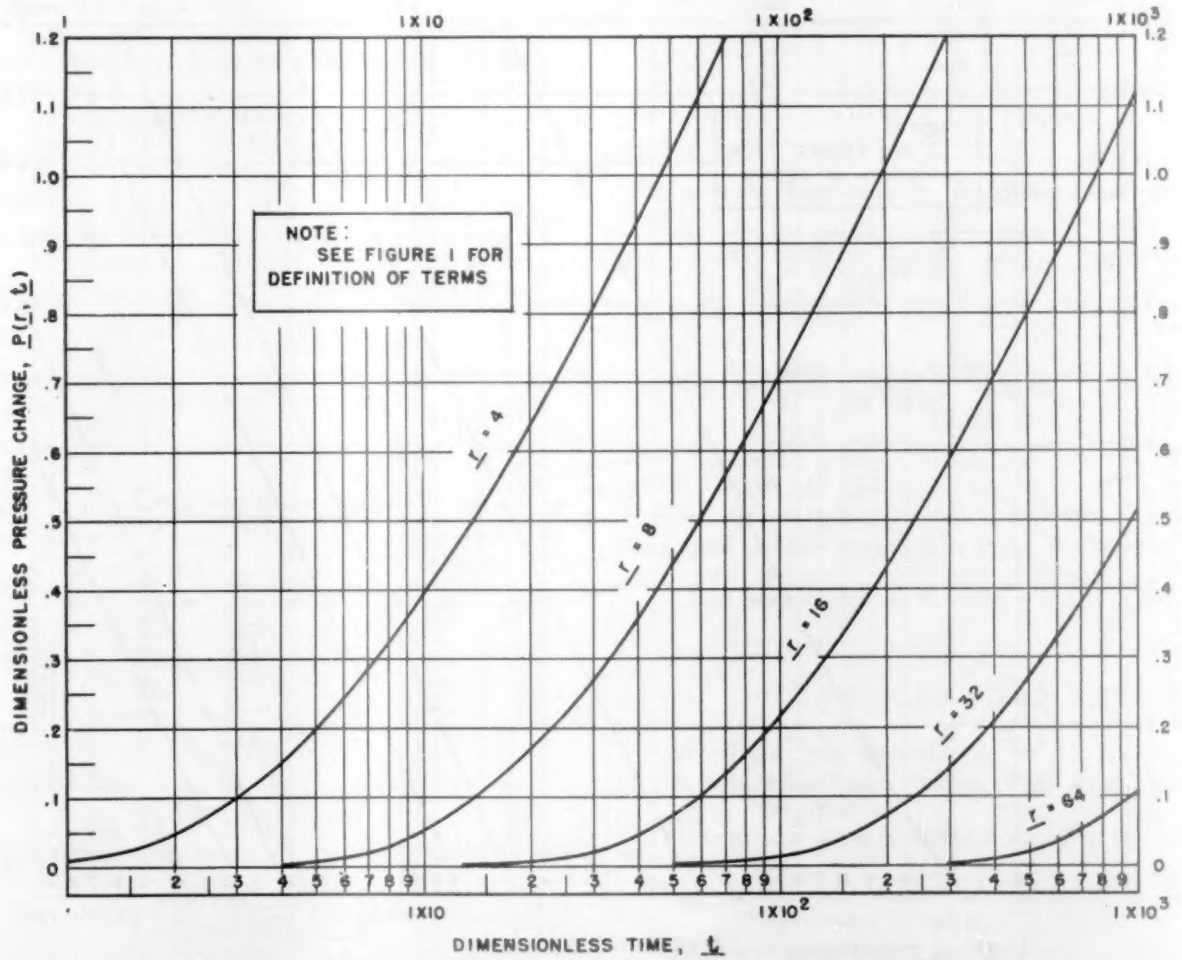

FIG. 2—PRESSURE DISTRIBUTION—INFINITE RADIAL SYSTEM—CONSTANT RATE CASE.

$$P_{Ab}(t_n) =$$

$$\sum_{i=0}^{n-1}\left[P_{Bb}(t_{i+1}) - P_{Bb}(t_i)\right]\underline{P}(r_B, t_n - t_i) \quad . \quad . \quad . \quad . \quad (10)$$

$$P_{Ba}(t_n) =$$

$$\sum_{i=0}^{n-1}\left[P_{Aa}(t_{i+1}) - P_{Aa}(t_i)\right]\underline{P}(r_A, t_n - t_i) \quad . \quad . \quad . \quad . \quad (11)$$

$\underline{P}\ (\underline{r}, \underline{t})$ is dimensionless pressure drop in the aquifer resulting from unit pressure drop in oil field, and can be obtained from Andrew Gemant's[12] constant pressure solution. Inserting $n = 1$ permits the evaluation of $P_{Aa}(t_1)$ and $P_{Bb}(t_1)$. This step entails solving four algebraic equations in four unknowns. Similarly inserting $n = 2, 3, 4 \ldots$ gives values of $P_{Aa}(t)$ and $P_{Bb}(t)$ for all time instants. The production rate of oil field A is then predicted from $P_{Aa}(t)$ and Equation 7. Similarly $P_{Bb}(t)$ is used to predict the production rate of B.

The above analyses are readily extended to cover multiple oil fields in a common aquifer, and are subject to the following considerations:

1. It was tacitly implied that the rate of water influx and the rate of production in reservoir barrels are equal. In case this assumption is not justified, more accurate predictions can be obtained by employing an iterative scheme. The procedure outlined earlier is used first to yield preliminary predictions. Then, the rate of water-influx is calculated from the preliminary predicted pressure and material balance equations, taking into account the compressibility of the oilfield contents.* The water-influx rates thus obtained replace the production rates in the above analysis to secure more accurate predictions.

2. The rate of production and the pressure drop may be represented by a stepwise variation as a function of time, provided that the step intervals are not taken to be too large.

ILLUSTRATIVE EXAMPLE

In the present paper no attempt has been made to apply this method on an actual field case. However, an illustrative example is presented to demonstrate the methods and procedures to be followed in the solution of typical interference problems. It is planned to apply this method to actual field cases; these results will be presented in a later paper.

Consider the case of a reservoir system comprised of two oil fields, A and B, which are located in an extensive aquifer and the distance between their centers is 7.98 miles. A and B enclose 2,000 and 8,000 acres of surface area, respectively, and are produced under complete water drive. The pressure-production

*This includes oil, gas, connate water and rock compressibility.

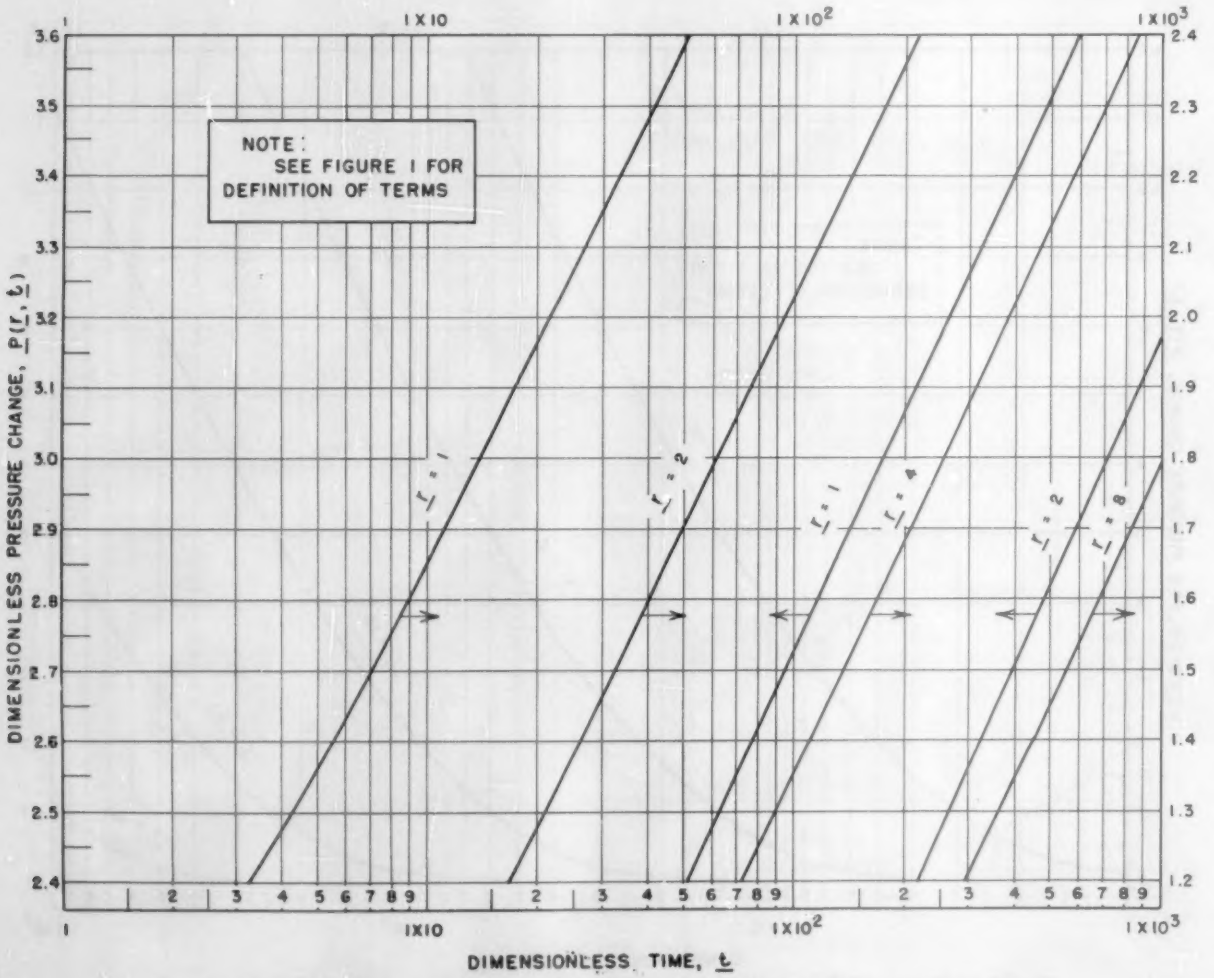

FIG. 3—PRESSURE DISTRIBUTION—INFINITE RADIAL SYSTEM—CONSTANT RATE CASE.

history of these fields, given in three-month increments, is shown in Figs. 4 and 5. Note that field A has been produced for the past four years and field B for the past two. The original pressure in the reservoir system was 4,000 psig, while the current pressure is 3,219 and 3,220 psig in A and B, respectively. The system is further characterized by the following physical properties;

$k = 212$ md, $f = 0.22$
$h = 84$ ft, $B = 1.15$ bbl/STB
$C_w = 5.0 \times 10^{-6}$ per psi, $\mu = 0.30$ cp

Let it be required to predict the pressure in both fields if A were produced with the present rate of 75,000 and B at 120,000 STB/D.

If the contribution of the oil compressibility to the energy of the system is neglected, and if it is assumed that every reservoir barrel of crude oil removed from the oil fields is replaced by a reservoir barrel of water from the aquifer, then the problem may be solved directly by utilizing Equation 6.

Since μ, B, k, h, and q are known quantities, only the dimensionless pressure change terms must be determined to solve the problem. This is done by first calculating the appropriate dimensionless time and radius and then locating the corresponding dimensionless pressure-change in the charts. Note that the numerical values of the time, t, and consequently the dimensionless time, t_D are always referred to the discovery date of the oil field under examination. The predicted performance is shown in Figs. 4 and 5.

As a sample calculation of the former step the pressures eight years hence are determined as follows:
Field A:

$$t_n = 12 \text{ years} = 4{,}383 \text{ days}$$

$$\underline{t_D} = (4.56)\ (10^{-1})\ \frac{kt_n}{f\mu C_w A} =$$

$$\frac{(4.56)\ (10^{-1})\ (212)\ (4{,}383)}{(.22)\ (.30)\ (5\times10^{-6})\ (2{,}000)}$$

$$= 642.0$$

$$r = 7.98 \text{ miles}$$

$$r_{wa} = \sqrt{\frac{2{,}000}{640\ \pi}} = .997 \text{ miles}$$

$$\underline{r_A} = \frac{7.98}{.997} = 8$$

TABLE 1 — CALCULATION OF PRESSURE CHANGES IN OILFIELDS A AND B DUE TO PRODUCTION FROM OILFIELD A

t_i days	$q_A(t_{i+1}) - q_A(t_i)$ STB/D	$\underline{t_i}$	$642 - \underline{t_i}$	$\underline{P}(642 - \underline{t_i})$	$\underline{P}(8{,}642 - \underline{t_i})$
		dimensionless time		dimensionless Pressure Change	
0	14,000	0.0	642.0	3.64	1.57
90	10,000	13.2	628.8	3.62	1.56
181	5,500	26.5	615.5	3.61	1.55
273	10,500	40.0	602.0	3.60	1.54
365	12,000	53.5	588.5	3.59	1.53
455	— 7,500	66.6	575.4	3.58	1.52
546	15,500	80.0	562.0	3.57	1.51
638	4,000	93.4	548.6	3.56	1.50
730	4,000	106.9	535.1	3.55	1.49
4383		642.0			

Substituting these values in the following equations,

$$P_{Aa} = (887.6)\ \frac{(0.30)\ (1.15)}{2\pi\ (212)\ (84)} \sum_{i=0}^{8} \left[q_A(t_{i+1}) - q_A(t_i)\right]$$

$$\underline{P}(1{,}642\text{-}\underline{t_i})$$

$$P_{Ba} = (887.6)\ \frac{(0.30)\ (1.15)}{2\pi\ (212)\ (84)} \sum_{i=0}^{8} \left[q_A(t_{i+1}) - q_A(t_i)\right]$$

$$\underline{P}(8{,}642\text{-}\underline{t_i})$$

Yields $P_{Aa} = 739.5$ psi
$P_{Ba} = 315.1$ psi

Field B:

$$t_n = 10 \text{ years} = 3{,}653 \text{ days}$$

$$\underline{t_D} = (4.56)\ (10^{-1})\ \frac{kt_n}{f\mu C_w A} =$$

$$\frac{(4.56)\ (10^{-1})\ (212)\ (3{,}653)}{(.22)\ (.30)\ (5\times10^{-6})\ (8{,}000)}$$

$$= 133.8$$

$$r = 7.98 \text{ miles}$$

$$r_{wb} = \sqrt{\frac{8{,}000}{640\ \pi}} = 1.994 \text{ miles}$$

$$\underline{r_B} = \frac{7.98}{1.994} = 4$$

TABLE 2 — CALCULATION OF PRESSURE CHANGE IN OILFIELDS B AND A DUE TO PRODUCTION FROM OILFIELD B

t_i days	$q_B(t_{i+1}) - q_B(t_i)$ STB/D	$\underline{t_i}$	$133.8 - \underline{t_i}$	$\underline{P}(1{,}133.8 - \underline{t_i})$	$\underline{P}(4{,}133.8 - \underline{t_i})$
		dimensionless time		dimensionless Pressure Change	
0	20,000	0.0	133.8	2.86	1.49
90	18,000	3.3	130.5	2.85	1.48
181	14,000	6.6	127.2	2.83	1.46
273	19,500	10.0	123.8	2.82	1.45
365	18,500	13.4	120.4	2.81	1.44
456	— 6,000	16.7	117.1	2.80	1.42
547	27,000	20.0	113.8	2.78	1.41
639	8,000	23.4	110.4	2.77	1.40
731	1,000	26.8	107.0	2.75	1.39
3653		133.8			

Substituting these values in the following equations,

$$P_{Bb} = (887.6)\ \frac{(0.30)\ (1.15)}{2\pi\ (212)\ (84)} \sum_{i=0}^{8} \left[q_B(t_{i+1}) - q_B(t_i)\right]$$

$$\underline{P}(1{,}133.8 - \underline{t_i})$$

$$P_{Ab} = (887.6)\ \frac{(0.30)\ (1.15)}{2\pi\ (212)\ (84)} \sum_{i=0}^{8} \left[q_B(t_{i+1}) - q_B(t_i)\right]$$

$$\underline{P}(4{,}133.8 - \underline{t_i})$$

Yields $P_{Bb} = 925.7$ psi
$P_{Ab} = 475.4$ psi

Thus, total pressure drop in A = $P_{Aa} + P_{Ab} = 1{,}214.9$ psi, and
total pressure drop in B = $P_{Bb} + P_{Ba} = 1{,}240.8$ psi

NOMENCLATURE

E_1 = Exponential integral.
K_n = Modified Bessel function of the second kind and n*th* order.
P_{Aa} = Pressure drop in oilfield A due to its production.
P_{Ab} = Interference pressure drop at oilfield A due to producing oilfield B.
P_A = Total pressure drop in oilfield A.
$P(r, t)$ = Pressure drop at radius, r, and time, t.

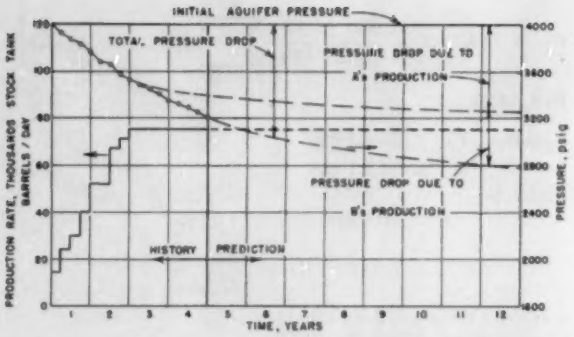

FIG. 4—OIL FIELD "A"—RESERVOIR PERFORMANCE—HISTORY AND PREDICTION.

$P(r, t)$ = Dimensionless pressure drop at dimensionless time t and radius r.
$q_A(t)$ = Production rate of oilfield A at time t.
r_{wa} = Radius of oilfield A.
r = Dimensionless radial distance, equals $\frac{r}{r_w}$.
r_A = Dimensionless distance between centers of oilfields A and B in multiples of r_{wa}.
t = Dimensionless time, equals $kt/f\mu C_w r_w^2$.
V = Dimensionless potential drop.
$\phi(r, t)$ = Reduced pressure, equals p/p_i.

APPENDIX

LAPLACE TRANSFORM AND CONTINUOUS POINT SINK

Laplace transform of $P(r, t)$ is defined as,

$$\bar{P}(r, s) = \int_0^\infty e^{-st} P(r, t)\, dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

When applied to Equation 5 of the text for the constant rate case, it gives

$$\bar{P}(r, s) = \frac{K_o(r\sqrt{s})}{s^{3/2} K_1(\sqrt{s})} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where K_o and K_1 are modified Bessel functions of the second kind. For small and large t, Equation 2 is simplified and the ensuing inverse transforms are readily evaluated.

If t is small, the operator, s, is large and $K_m(z)$ is reduced to[14],

$$K_m(z) = \sqrt{\frac{\pi}{2z}}\, e^{-z}$$

substituting for K_o and K_1 in Equation 2, it becomes

$$\bar{P}(r, s) = \frac{e^{-(r-1)\sqrt{s}}}{\sqrt{r}\, s^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The inverse Laplace transform of Equation 3 is[7],

$$P(r, t) = \frac{2\sqrt{t}}{\sqrt{r}}\, ierfc\, \frac{r-1}{2\sqrt{t}} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where $ierfc\, x = \frac{e^{-x^2}}{\sqrt{\pi}} - x\, erfc\, x$

and $erfc\, x = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-\zeta^2} \partial\zeta$

$ierfc\, x$ is readily evaluated from "Tables of the error function and its derivative"[15]. The relation given by Equation 4 is accurate for $t \leq .01$.

If t is large, the operator s is small and $K_m(z)$ is given by

$$K_o(z) = -\left(ln\, \frac{z}{2} + \gamma\right), \; K_1(z) = \frac{1}{z} \quad . \quad . \quad (5)$$

where γ "Euler's constant" = 0.57722. Again substituting for K_o and K_1 in Equation 2, it reduces to

$$\bar{P}(r, s) = -\frac{ln\, s}{2s} + \frac{ln^2/r - \gamma}{s} \quad . \quad . \quad . \quad . \quad (6)$$

The inverse Laplace transform of Equation 6 is given by Carslaw and Jaeger[7],

$$P(r, t) = \frac{1}{2}\left[ln\, \frac{4t}{r^2} - \gamma\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

This relation is accurate for $\frac{4t}{r^2} \geq 2{,}000$

Equation 7 is also a solution of the continuous point sink for large t. The continuous point sink solution, originally developed by Lord Kelvin, is expressed as

$$P(r, t) = \frac{1}{2}\left[-E_1\left(-\frac{r^2}{4t}\right)\right] \quad . \quad . \quad . \quad . \quad (8)$$

where $-E_1\left(-\frac{r^2}{4t}\right) = \int_{\frac{r^2}{4t}}^\infty \frac{e^{-x}}{x}\, \partial x$

The "E_1" function is known as the exponential integral and its values are given in "Tables of sine, cosine and exponential integral"[16]. For $\frac{4t}{r^2} \geq 2{,}000$ the exponential integral reduces to $ln\, \frac{4t}{r^2} - \gamma$, and the pressure gradient becomes $\left(\frac{\partial P}{\partial r}\right)_{r\,=\,1,\; t \geq 500} = -1$

Consequently, only for $t \geq 500$ the continuous point sink solution describes accurately the solution to a "ring" of production.

It is evident that the continuous point sink solution does not apply for the determination of the pressure change when t is small. However, when the radius, r_w,

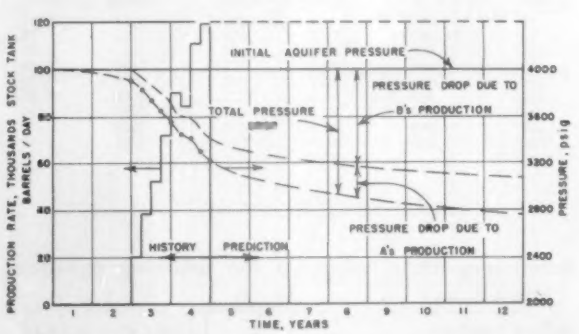

FIG. 5 — OILFIELD "B" RESERVOIR PERFORMANCE — HISTORY AND PREDICTION.

is small, such as a well radius, even small values of the absolute time, t, will give large values of the dimensionless time, $\underline{t}$, and the continuous point sink is applicable. On the other hand, in treating oil fields (in which case r_w can have a large numerical value) the value of $\underline{t}$ can be easily less than 500 even for large values of absolute time, t.

In recapitulating,

$$\underline{P}(\underline{r}, \underline{t}) \begin{cases} = \dfrac{2\sqrt{\underline{t}}}{\sqrt{\underline{r}}}\, ierfc \dfrac{\underline{r}-1}{2\sqrt{\underline{t}}} & \text{for } \underline{t} \leq .01 \\ = \dfrac{1}{2}\left[-E_i\left(\dfrac{-\underline{r}^2}{4\underline{t}}\right)\right] & \text{for } \underline{t} \geq 500 \end{cases} \quad \ldots \quad (9)$$

Therefore, to bridge the gap between $\underline{t} = .01$ and 500, analog and digital computers are used.

Analog Computation

Analog computation based on the fundamental equation for flow of electric current in a dielectric medium[8], was performed by the use of a resistance-capacitance type analyzer. The reservoir system under consideration was divided into segments by concentric circles and each segment was represented by a condenser and a resistance. Constant current, i, was drawn from the circuit and the voltage was recorded as a function of time for every segment. A sufficient number of segments was included in the circuit such that the last condenser showed no voltage drop during the time interval of interest, thus simulating an extensive aquifer. Because of practical considerations, 10 was the maximum number of condensers used. The results obtained from the analog computer are approximate due to truncation error introduced by the limited number of segments available in the analog computer used, and the limitations imposed by the available recording instruments.

Digital Computation

Digital computation was employed to achieve better accuracy. The diffusivity equation was translated to a set of difference equations which were solved simultaneously with the aid of a digital computing machine "Datatron." Difference equations:

$$\text{Let } u = ln\, \underline{r}, \text{ and } \phi = \frac{p}{p_i} \quad \ldots \quad (10)$$

where ϕ is reduced pressure and p_i is initial pressure in the aquifer. Substituting Equation 10 in Equation 5 of the text, it becomes

$$\frac{\partial^2 \phi}{\partial u^2} = e^{2u} \frac{\partial \phi}{\partial \underline{t}} \quad \ldots \quad (11)$$

The step-by-step calculations of the pressure change were performed on the finite-difference form of this equation. Dividing the aquifer by a number, n, of concentric circles and denoting the time stations by m, Equation 11 takes the following finite-difference form[17,18]

$$\frac{1}{2}\left\{\left[\frac{\phi_{n-1} - 2\,\phi_n + \phi_{n+1}}{(\triangle u)^2}\right]_m + \left[\frac{\phi_{n-1} - 2\,\phi_n + \phi_{n+1}}{(\triangle u)^2}\right]_{m+1}\right\} = e^{2nu}\left\{\frac{\phi_{n,m+1} - \phi_{n,m}}{\triangle \underline{t}}\right\}$$

By rearranging the terms and choosing equal $\triangle u$ increments, the above equation can be rewritten as

$$\left\{\phi_{n-1} - 2\left[1 + \frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2n\triangle u}\right]\phi_n + \phi_{n+1}\right\}_{m+1} = \left\{-\phi_{n-1} + 2\left[1 - \frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2n\triangle u}\right]\phi_n - \phi_{n+1}\right\}_m \quad \ldots \quad (12)$$

From the condition of constant rate and Equation 10, it follows that

$$\left(\frac{\partial \phi}{\partial u}\right)_{u=0} = H \text{ "constant"} \quad \ldots \quad (13)$$

and the rate of water influx becomes

$$q = \frac{2\pi kh}{\mu}\, p_i\, H$$

The pressure distribution associated with this rate is converted directly to the corresponding pressure change, $\underline{P}(\underline{r}, \underline{t})$, thus

$$\underline{P}(\underline{r}, \underline{t}) = \frac{1 - \phi}{H} \quad \ldots \quad (14)$$

For $n = 1$

$$\phi_{n-1,m} = \phi_{0,m} = \phi_{w,m}$$

where ϕ_w is reduced field pressure. From Equation 13 and Taylor's expansion we get,

$$\phi_{1,m} = \phi_{w,m} + (\triangle u)H + \frac{(\triangle u)^2}{2!}\left(\frac{\partial^2 \phi}{\partial u^2}\right)_{u=0} + \quad \ldots \quad (15)$$

Expressing $\left(\dfrac{\partial^2 \phi}{\partial u^2}\right)_{u=0}$ in difference form, Equation 15 becomes

$$\phi_{w,m} = \frac{4}{3}\,\phi_{1,m} - \frac{1}{3}\,\phi_{2,m} - \frac{2}{3}\,H\triangle u$$

By substituting the above relation in Equation 12 for $n = 1$, it takes the form

$$\left\{\left[-1 - 3\,\frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2\triangle u}\right]\phi_1 + \phi_2\right\}_{m+1} = \left\{\left[1 - 3\,\frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2\triangle u}\right]\phi_1 - \phi_2\right\}_m \quad \ldots \quad (16)$$

The computations are based on Equations 12 and 16.

A technique was followed by which 30 difference-equations were set to describe a limited radial system. The pressure was computed for consecutive time stations $t_1, t_2, t_3, \ldots$ up to t_n at which the outer boundary showed the first sign of pressure decline. Pressures corresponding to t_{n-1} were used as boundary values for a larger radial system. By using this procedure it was possible to take small radial increments with a limited number of difference-equations. Values of $\triangle \underline{t}$ were chosen progressively smaller till the computed values of $\underline{P}(\underline{r}, \underline{t})$ showed no change in the third decimal place. The values of $\underline{P}(\underline{r}, \underline{t})$ thus obtained are accurate to three decimal places. This is adequate accuracy considering the degree of uncertainty associated with most properties of reservoir systems.

It is self evident that Equations 12 and 16 are suitable to secure the pressure distribution associated with a limited radial system for all values of dimensionless time, t. One might also add that the solution for the constant pressure case is readily computed from Equation 12 and an auxiliary equation stipulating constant pressure in the oil field. The auxiliary equation is given by

$$\left\{-1 + 2\left[\frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2\triangle u}\right]\phi_1 + \phi_2\right\}_{m+1} = \left\{1 - 2\left[\frac{(\triangle u)^2}{\triangle \underline{t}}\, e^{2\triangle u}\right]\phi_1 - \phi_2\right\}_m \quad \ldots \quad (17)$$

The case where the permeability varies with radial distance is being examined by using a modified form of Equation 12 to account for the permeability variation.

It might be well to mention that several attempts were made before the solution was perfected to the

desired degree of accuracy. Preliminary computations were performed neglecting the third term in the right hand side of Equation 15, and led to values of $P(r, t)$ which included considerable error especially for small t.

CONCLUSIONS

Non-steady state pressure distribution in an extensive aquifer due to constant rate of production from a circular sink has been developed partially from mathematical considerations and partially from analog and digital computations. By virtue of the superposition theorem, the pressure distribution provides a practical analytical method for evaluating the interference effect in water-drive oil fields sharing a common extensive aquifer.

The case of production near a fault is treated by applying the method of images. In addition, provisions are made for treating oil fields, which are produced by partial water-drive.

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WETTABILITY VERSUS DISPLACEMENT in WATER FLOODING in UNCONSOLIDATED SAND COLUMNS

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ABSTRACT

A series of water floods was made on laboratory prepared unconsolidated sand columns to study the effects on oil recovery of the solid-water-oil contact angle, the oil-water interfacial tension, flood rate, and oil viscosity.

A procedure was developed for treating silica sand with silicone polymer to produce surfaces of varying degrees of wettability as evaluated by measuring the contact angle on a flat silica plate that had been simultaneously treated with the sand. Fluid interfacial tensions were changed by the use of surface active agents in the flood water. Water-wet, oil-wet, and intermediate wettability systems were studied at high and at low values of interfacial tension, at several flood rates, and with oils of different viscosities.

For both oil-wet and water-wet systems and a low viscosity oil, recoveries were functions of the oil-water interfacial tension; also, increase in flood rate resulted in increased oil recoveries. High interfacial tension floods were more efficient than low interfacial tension floods on water-wet systems, while low interfacial tension floods were more efficient on oil-wet systems. Intermediate or neutral wettability systems were less sensitive to rate of flood advance and interfacial tension than either oil-wet or water-wet systems.

The effects of surface forces on oil recovery for high viscosity oils were not so well defined as for low viscosity oils.

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INTRODUCTION

Reservoir rock surfaces vary in their wettability[1], some being water-wet while others are apparently oil-wet. The factor of wettability enters into reservoir performance in both primary and secondary recovery, and into laboratory measurements of capillary pressure, connate water saturation, and relative permeabilities.[2] In theory, the degree of wettability is measured by the contact angle for the system solid-water-oil. A water-wet system is defined as one in which the advancing water contact angle is less than 90°. An oil-wet system is one in which the advancing water contact angle is greater than 90°.[3]

[1]References given at end of paper.

The surface forces in a solid-water-oil system are related by the Young-Dupree equation as follows[4]:

$$A_{sw} - A_{so} = \sigma_{so} - \sigma_{sw} = \sigma_{ow}\cos\Theta = -\Delta F \quad . \quad . \quad . \quad (1)$$

These surface forces are commonly expressed as the difference in adhesion tension, or the product of the water-oil interfacial tension and the contact angle. If the contact angle is less than 90°, the adhesion tension difference is positive and oil displacement by water from a solid surface will be spontaneous and favored by a high oil-water interfacial tension. If the angle is greater than 90° the displacement will not be spontaneous but will require less energy the lower the oil-water interfacial tension. The contact angle and interfacial tension also appear in the capillary pressure equation[5]:

$$P_c = 2\sigma\cos\Theta/r \quad . \quad . \quad . \quad . \quad (2)$$

The quantity $\sigma\cos\Theta$ was used by Rapoport and Leas[6] as a factor in the generalized form of their "scaling coefficient." Warren and Calhoun[7] presented the results of $\sigma\cos\Theta$ on oil recovery in oil-wet systems and correlated their data using a "scaling coefficient" suggested by Jones-Parra and Calhoun.[8] The "scaling coefficients" were advanced to help correlate the effects of the variables influencing oil recovery by

external drive and specifically to clarify the effect of injection rate upon oil recovery in laboratory flooding tests. The effect of increased injection rate has been reported by various authors to increase, to decrease, and not to affect oil recovery. Levine[9] as well as Rapoport and Leas[6] cite several references as to the effect of injection rate on recovery.

It was the object of this work to investigate separately the effects of contact angle and interfacial tension as measured external to the system on oil recovery in water flooding of unconsolidated sand columns at various injection rates and at different oil-water viscosity ratios. The contact angle was controlled by treating the sand with silicone to render the sand surface to varying degrees of wettability. Interfacial tension was altered by the addition of surface active agents to the flood water.

EXPERIMENTAL PROCEDURES

Materials

The flow models were made of Lucite tubes 59 cm long, 2.52 cm in diameter, and 295 ml capacity. The tubes were packed with 80-120 mesh silica sand to an average permeability of 11 darcies to oil and average porosity of 33.5 per cent. The surface area of the sand was calculated from the porosity and permeability by the Kozeny equation[10] as 452 cm^2/gm of sand.

Oils of three different viscosities were used. A decane-dodecane paraffinic hydrocarbon, Soltrol C, was used in a majority of the experiments. Two oils of 32 cp viscosity but of different interfacial tensions against water, and an oil of 265 cp viscosity, were also used. Properties of the oils are listed in Table 1.

Tap water of 0.895 cp viscosity at the temperature of the experiments, 25°C, or tap water containing dissolved surfactant, were the displacing phases. The surfactants were Igepal CO-630 and Igepal CO-880 from Antara Chemicals, and Pluronic F-68 from Wyandotte Chemicals Corp. These are non-ionic type surfactants but with differing degrees of interfacial activity against water.

The silicone used to treat the sand surfaces was Dow-Corning DC-1107, a 20-40 centistoke viscosity methylsiloxane polymer.

Procedure

The sand was treated with a known weight of silicone dissolved in isoproyl alcohol. Enough alcohol was used to give a thick slurry, about 200 ml per 1,000 gm of sand. The sand slurry was mixed thoroughly and after standing overnight, the alcohol was removed by vacuum evaporation with frequent mixing. After removal of the alcohol the silicone was set by heating at 150°C for two hours. A flat silica plate was processed along with the sand. A measure of the oil wettability of the sand surface was then available by measuring the contact angle on the silica plate.

The silica plate was placed in a rectangular optical cell and allowed to stand overnight under oil. The advancing silica-water-oil contact angle was formed by placing small drops, about 2 to 4 mm in diameter, of the displacing phase on the silica plate. An image of the solid and drop was shown on a screen by projecting light through the cell and using a 4 by 5 in. Graphic camera with the back removed as a projector. The angle between the solid and the water-oil interface measured through the water was obtained with a protractor from the image. Angles were measured at two to five minutes, at 30 minutes, at one hour, and at 24 hours after the formation of the drop.

Interfacial tensions were measured with a DuNouy vernier tensiometer. The ring was cleaned by flaming and placed in contact with the aqueous phase prior to each measurement. The ring was pulled from the aqueous phase into the oil through interfaces at 15 to 30 minutes' age. Readings were corrected from a curve obtained by running the surface tension of liquids of known value on the instrument. Interfacial tension as well as contact angle determinations were made at approximately 25°C.

Prior to the flooding experiments, the Lucite tubes were packed with sand in a standard manner, evacuated, filled 100 per cent with oil and allowed to stand for 18 to 24 hours. The oil-filled columns were then flooded horizontally at constant rates using a quadruplex Milton Roy Minipump. Fresh sand was used to prepare a new model for each flood. Oil production was observed visually at water breakthrough and periodically thereafter until eight pore volumes of water had been injected in the case of the Soltrol C systems and 15 pore volumes in the cases of the higher viscosity oils.

TABLE 1—PROPERTIES OF HYDROCARBONS USED IN WATERFLOOD EXPERIMENTS

Hydrocarbon	Specific Gravity, 25°C	Viscosity, 25°C Centipoises	Oil-Water Viscosity Ratio	Interfacial Tension Vs. Water, 25°C Dynes/cm
Soltrol C	0.754	1.31	1.46	44
32 CP Neutral Oil	0.852	32	35.8	16.8
32 Cp Oil Blend	0.836	32	35.8	34.5
265 Cp Neutral Oil	0.873	265	296	35.8

EXPERIMENTAL RESULTS AND DISCUSSION

Surface Properties

The wettability of the systems studied is designated by the value of the contact angle. The variation in contact angle with silicone treatment for the silica, water, Soltrol C system is given in Table 2. The data in Table 2 give the average value of the contact angle and deviation from the average as a result of several treatments on each system. Precision of measurement of the contact angle was within 5°, although in some cases the actual deviation from the contact angle may have been as high as 15°, due possibly to slight differences in treatment. The system referred to as water-wet consisted of untreated sand, the oil-wet system was highly silicone treated, whereas the neutral or intermediate system was given an approximately monomolecular coating of silicone. The quantity of silicone required for a monomolecular coating of the sand was calculated to be 0.0266 mg/gm of sand. This value is based on the sand surface area calculated from porosity-permeability data and 1.7 sq m as the area occupied by 1 mg of silicone polymer.[11] Contact angles ranged from 45 to 160°, as measured through the water.

Contact angle data for silica, surfactant solution, and Soltrol C are listed in Table 3.

The value of interfacial tensions are listed with the individual runs in Figs. 1 through 7 for Soltrol C

TABLE 2—SILICA-WATER-SOLTROL C CONTACT ANGLES

Mg Silicone Per Gm Sand	No. Silicone Layers	Average Contact Angles, Degrees 2-5 Min.	30 Min.	1 Hr.	24 Hrs.
0	0	45±15	30	28	25±10
0.0125	0.47	62±10	60	58	46± 6
0.025	0.94	85±10	82	75	71± 6
0.05	1.88	108±10	100	95	90± 5
0.10	3.76	140±10	127	127	115±15
1.0	37.6	157± 5	157	157	154± 5

TABLE 3—SILICA SURFACTANT SOLUTION—SOLTROL C CONTACT ANGLES

Mg Silicone Per Gm Sand	Surfactant Solution, Conc. PPM	Average Contact Angle, Degrees 2-5 Min.	24 Hrs.
0	500 CO-630	58±10	25±10
0	1000 CO-630	60±10	30±10
0	1000 CO-880	35±10	25±10
0	1000 F-68	35±10	25±10
0.0125	500 CO-630	65± 5	52± 5
0.025	500 CO-630	78±10	64±10
0.025	1000 CO-630	80±10	65±10
0.050	500 CO-630	85±10	70±10
0.10	500 CO-630	140±10	125±10
1.0	500 CO-630	160± 5	160± 5
1.0	1000 CO-630	160± 5	160± 5
1.0	500 CO-880	160± 5	160± 5
1.0	1000 F-68	160± 5	160± 5

and in Table 4 for high viscosity oils. Interfacial tensions varied from 44 to 2.8 dynes/cm in the Soltrol C floods and from 35.8 to 1.2 dynes/cm for the high viscosity oil floods.

Soltrol C Floods

Results of oil displacement runs on sand columns 100 per cent saturated with Soltrol C are given in Figs. 1 through 7.

The effect of wettability for high interfacial tension floods at a water injection rate of 50 ml/hour (approximate linear advance of 1 ft/hour is shown in Fig. 1. These data suggest that oil recovery at water breakthrough is not affected by the advancing contact angle if it is less than 90°. At the flood rate used, however, oil recovery after breakthrough was greater for lower values of the contact angle. Oil recovery decreased at breakthrough for contact angles above 90° as the angles increased.

Water floods on a water-wet system at four interfacial tensions and a 50 ml/hour injection rate are given in Fig. 2. These results indicate that high interfacial tension floods are more efficient than low interfacial tension floods on water-wet or untreated system. Interfacial tension has an opposite effect on oil-wet systems as shown in Fig. 3 where oil

TABLE 4 — SUMMARY OF HIGH VISCOSITY OIL DISPLACEMENTS

Flood No.	Oil-Water Viscosity Ratio	Silicone Treatment Mg/Gm	Interfacial Tension Dynes/cm	Injection Rate Ml/Hr	Contact Angles At B.T.	Contact Angles At 15 W_i	Res. Oil Satn, % Pore Space At Water BT	Res. Oil Satn, % Pore Space 2 W_i	Res. Oil Satn, % Pore Space 5 W_i	Res. Oil Satn, % Pore Space 8 W_i	Res. Oil Satn, % Pore Space 15 W_i	Scaling Factors * At B.T. $LV\mu_w\sigma/\mu_o\cos\theta$	Scaling Factors * At 15 W_i $LV\mu_w\sigma/\mu_o\cos\theta$
50	35.8	0	34.5	10.7	83	53	28.1	19.2	14.7	12.6	11	16.69	3.38
51	35.8	0	34.5	101	83	53	80.5	52.5	34.8	27.0	19.6	157.6	31.9
52	35.8	0	34.5	340	83	53	82.9	52.8	36.0	28.0	19.8	530	107
53	35.8	0	16.8	10.0	83	53	26.2	25.0	24.5	24.3	24.0	7.60	1.54
54	35.8	0	16.8	29.1	83	53	33.4	29.7	27.5	26.1	25.0	22.1	4.48
55	35.8	0	16.8	49.8	83	53	67.7	55.5	46.2	39.0	25.3	37.83	7.66
56	35.8	0	16.8	98.3	83	53	74.1	55.1	39.1	31.0	25.0	74.68	15.13
57	35.8	0	16.8	338	83	53	80.2	53.5	39.2	31.2	21.8	257	52.1
58	35.8	0	1.2	10.1	83	53	28.8	25.5	22.2	20.4	18.0	0.548	0.111
59	35.8	0	1.2	25.6	83	53	47.5	38.3	31.4	27.0	20.5	1.39	0.281
60	35.8	0	1.2	53.6	83	53	65.4	48.2	33.8	26.7	19.2	2.91	0.589
61	35.8	0	1.2	96.5	83	53	74.4	53.0	48.0	47.2	46.0	5.24	1.06
62	35.8	0	1.2	330	83	53	80.4	51.8	44.2	42.0	40.8	17.91	3.63
63	35.8	0.025	34.5	10.4	122	118	35.6	35.0	34.4	34.2	33.0	-0.0031	-0.0035
64	35.8	0.025	34.5	98.0	122	118	79.4	54.5	38.3	30.0	19.7	-0.0294	-0.0332
65	35.8	0.025	34.5	341	122	118	85.9	57.0	38.8	29.3	18.2	-0.102	-0.115
66	35.8	0.025	16.8	10.0	122	118	27.3	27.0	26.3	26.2	26.0	-0.0062	-0.00698
67	35.8	0.025	16.8	50.0	122	118	65.9	54.8	44.7	36.3	27.0	-0.0310	-0.0349
68	35.8	0.025	16.8	98.6	122	118	74.7	56.5	42.1	34.4	26.0	-0.0610	-0.0689
69	35.8	0.025	16.8	338	122	118	84.0	54.8	39.2	31.0	21.0	-0.209	-0.236
70	35.8	0.025	1.2	9.4	122	118	37.6	25.6	22.3	20.0	16.2	-0.0815	-0.0920
71	35.8	0.025	1.2	48.0	122	118	61.0	50.5	35.4	30.0	26.2	-0.416	-0.470
72	35.8	0.025	1.2	98.6	122	118	77.8	54.2	36.7	28.8	21.7	-0.855	-0.964
73	35.8	0.025	1.2	348	122	118	82.1	54.2	38.2	35.0	34.0	-3.02	-3.40
74	35.8	1.0	34.5	9.9	162	154	76.9	57.5	48.8	45.0	44.0	-0.0017	-0.0017
75	35.8	1.0	34.5	92.7	162	154	79.4	53.8	44.0	39.3	35.0	-0.0155	-0.0164
76	35.8	1.0	34.5	340	162	154	80.9	54.0	44.9	39.7	33.9	-0.0571	-0.0604
77	35.8	1.0	16.8	9.5	162	154	70.8	53.6	46.0	42.1	38.2	-0.0033	-0.0035
78	35.8	1.0	16.8	102	162	154	73.9	52.5	43.9	39.5	35.0	-0.0351	-0.0371
79	35.8	1.0	16.8	340	162	154	76.2	53.6	43.9	39.3	33.8	-0.117	-0.124
80	35.8	1.0	1.2	10.0	162	154	66.5	46.5	37.7	32.0	25.5	-0.0483	-0.0511
81	35.8	1.0	1.2	103	162	154	73.6	57.2	41.4	34.2	26.3	-0.498	-0.526
82	35.8	1.0	1.2	340	162	154	73.5	55.0	42.2	34.2	27.5	-1.642	-1.74
83	296	0	35.8	10.5	83	53	64.0	56.7	50.9	48.7	45.8	2.05	0.416
84	296	0	35.8	100	83	53	92.2	70.7	60.0	54.2	45.5	19.6	3.97
85	296	0	1.8	10.5	83	53	66.3	60.8	54.2	49.2	42.6	0.102	0.0209
86	296	0	1.8	98.8	83	53	92.3	73.7	66.8	62.5	60.0	0.971	0.197
87	296	0.025	35.8	9.6	122	118	77.8	74.4	72.2	71.0	69.2	-0.00033	-0.00037
88	296	0.025	35.8	98.3	122	118	95.1	75.2	66.4	61.0	53.1	-0.00344	-0.00388
89	296	0.025	1.8	10.3	122	118	78.2	66.6	54.1	47.8	40.0	-0.00718	-0.00810
90	296	0.025	1.8	99.3	122	118	92.9	69.7	60.0	58.7	57.5	-0.0693	-0.0782
91	296	1.0	35.8	9.9	162	154	92.3	73.2	64.4	59.1	54.1	-0.00019	-0.00020
92	296	1.0	35.8	100	162	154	87.6	71.8	63.7	59.9	55.2	-0.00195	-0.00206
93	296	1.0	35.8	99.6	162	154	87.8	71.2	63.5	59.0	—	—	—
94	296	1.0	1.8	10.7	162	154	92.6	80.0	72.8	69.0	64.0	-0.00409	-0.00432
95	296	1.0	1.8	10.3	162	154	91.9	81.3	74.0	69.5	—	—	—
96	296	1.0	1.8	101	162	154	79.0	69.0	62.0	57.3	49.7	-0.0389	-0.0411
97	296	1.0	1.8	99.5	162	154	82.8	70.0	62.2	57.0	—	—	—

* The scaling factor $LV\mu_w\sigma/\mu_o\cos\theta$ is for contact angles below 90°. For contact angles above 90° the scaling factor is $LV\mu_w/\mu_o\sigma\cos\theta$.

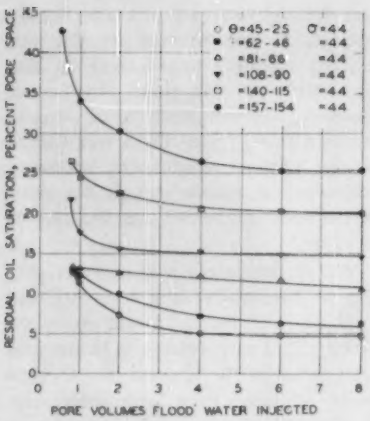

FIG. 1 — HIGH INTERFACIAL TENSION FLOODS ON VARYING WETTABILITY SOLTROL C SYSTEMS AT 50 ML/HR INJECTION RATE.

recovery increased as the interfacial tension was lowered. These results are as predicted by Equation 1. In the case of the water-wet system the spontaneity of oil displacement by water increases with $\sigma\cos\Theta$. For the oil-wet system, where $\cos\Theta$ is negative, less energy is required to displace oil as $\sigma\cos\Theta$ becomes smaller numerically.

The rate of water injection has an appreciable effect on oil recovery, especially at very low rates. This is shown for high and low interfacial tension floods on water-wet systems in Fig. 4. Oil recovery increased with rate up to a certain point, beyond which further rate increases had less effect on oil recovery. This stabilized recovery was reached at 15-25 ml/hour for high interfacial tension floods and 100 to 200 ml/hour for low interfacial tension floods. A maximum in oil recovery at water breakthrough was observed at 25 ml/hour for the high interfacial tension floods. This maximum in oil recovery for high interfacial tension floods as a function of rate may be explained by the tendency of water to imbibe into the smaller or tighter channels. At low flood rates flow channels are established by imbibition through the smaller channels. At slightly higher rates more water pushes into the larger channels as the flow capacity of the imbibition channels is exceeded. At still higher rates more of the injected water is carried by the larger channels, with the result that some oil is trapped and bypassed in the tight channels. The maximum oil recovery is observed, then, at the injection rate where water flows at the same rate of linear advance through large and small channels. In the case of low interfacial tension floods, channels once formed have less tendency to branch or expand due to lower capillary pressure difference between phases. This means a higher injection rate is required to create a flow pattern or system of channels equivalent to the high interfacial tension floods.

Fig. 5 shows that oil recovery increased with flood rates for both high and low interfacial tension floods on intermediate wettability systems. Stabilized recovery was reached at a rate of from 1 to 5 ml/hour for high interfacial tension floods and at 5 to 25 ml/hour for low interfacial tension floods. Maximum oil recovery was obtained at 5 ml/hour for the high and at 25 ml/hour for the low interfacial tension floods. For the neutral or intermediate wettability system there is no tendency for water to imbibe into the tighter channels and by-pass oil in the larger channels. As a result, water moves through the larger channels as well as the small channels in a piston-like displacement. This results in a low value of injection rate for stabilized recovery as compared to the water-wet system or the oil-wet system. The maximum oil recovery observed at the optimum injection rate, as well as the lower rate required for stabilized oil recovery with high interfacial tension floods, is believed due to the explanation offered in the preceding paragraph.

The effect of rate on oil recovery for oil-wet systems is presented in Fig. 6. Oil recovery became stable at about 100 ml/hour for both high and low interfacial floods. For oil-wet systems water does not imbibe but must be forced into all flow channels. Less pressure is required to penetrate large channels than small channels. At low rates water flows through the larger channels, while higher rates result in the penetration of smaller channels. As a result, oil recovery increases with flood rate.

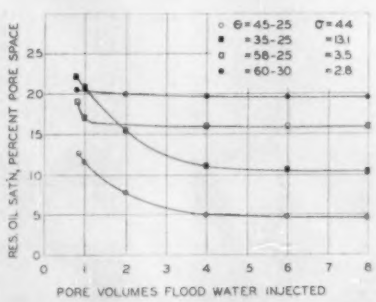

FIG. 2—VARYING INTERFACIAL TENSION FLOODS ON WATER-WET SOLTROL C SYSTEMS AT 50 ML/HOUR INJECTION RATE

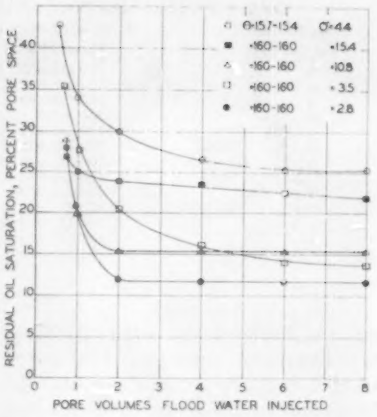

FIG. 3—VARYING INTERFACIAL TENSION FLOODS ON OIL-WET SOLTROL C SYSTEMS AT 50 ML/HOUR INJECTION RATE.

The effects of contact angle, interfacial tension, and rate on oil recovery at water breakthrough are summarized in Fig. 7. These data show that oil recovery for intermediate wettability systems is less sensitive to rate of water injection and to the oil-water interfacial tension than for either the water-wet or oil-wet systems. At rates above stabilized values, oil recovery was highest for low interfacial tension floods on intermediate wettability systems.

Several different combinations of variables were grouped in an effort to reduce experimental data to a common curve. One attempt is shown in Fig. 8 as $LV\mu_w\sigma/\mu_o\cos\Theta$ for contact below 90° and $LV\mu_w/\mu_o\sigma\cos\Theta$ for contact angle above 90°. These values are plotted against residual oil saturation at water breakthrough.

HIGH VISCOSITY OIL FLOODS

Water floods were made on three wettability systems using 32 cp oil. Three interfacial tensions and several rates were covered. Results are presented in Table 4.

The 32 cp oil systems are characterized by higher oil recoveries at water breakthrough at low rather than high flood rates. This result appeared visually to be due to channeling. Engelberts and Klinkenberg[12], who observed similar results, called the phenomenon "viscous fingering." Jones-Parra[13] reported this to be due to the fact that the inlet saturation distribution does not reach equilibrium at high rates. This channeling effect was not so pronounced on oil-wet systems. It was especially apparent for low interfacial tension floods on untreated and lightly silicone treated sands at higher injection rates. The severe channeling for low

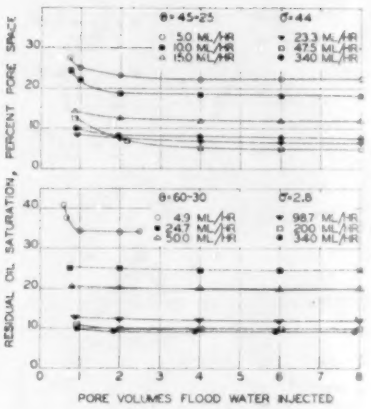

FIG. 4 — EFFECT OF RATE ON OIL RECOVERY FOR FLOODS ON WATER-WET SOLTROL C SYSTEMS.

interfacial tension floods is probably due to the low capillary pressure difference between the oil and water phases. This results in less channel branching than in the case of high interfacial tension floods.

For the untreated systems, a comparison of the average of residual saturations at 10, 100, and 340 ml/hour rates shows the high interfacial tension floods to be slightly less efficient than low interfacial tension floods at water breakthrough but more efficient at 15 pore volumes of injected water. Such a comparison for the 0.025 mg/gm treated systems (or neutral wettability) does not reveal any significant effect of interfacial tension on oil recovery. For oil-wet systems, oil recovery was higher at water breakthrough and at 15 pore volumes of injected water the lower the interfacial tension.

The results of water floods on three wettability systems saturated with 265 cp oil are given in Table 4. Oil recovery at water breakthrough decreased with rate for the untreated and 0.025 mg/gm treated systems whereas oil recovery increased with rate for the oil-wet system.

Attempts to correlate data for the high viscosity oils with Soltrol C were not successful except for oil-wet systems where the general grouping shown in Fig. 9 was obtained. This grouping shows the residual oil saturation at eight pore volumes of injected water for Soltrol C and 15 pore volumes of injected water for the high viscosity oils plotted against $LV\mu_w/\mu_o\sigma\cos\Theta$.

SUMMARY AND CONCLUSIONS

Water floods have been made on laboratory-prepared unconsolidated sand models to study the effects of the solid-water-oil contact angle, the oil-water interfacial tension, the water injection rate, and oil-water viscosity ratio on oil recovery. Advancing contact angles ranged from 35° to 160°, interfacial tensions from 1.2 to 44 dynes/cm, water injection rates from 1.2 to 400 ml/hour, and oil-water viscosity ratios from 1.46 to 296. The sand models of 59 cm length and 2.52 cm diameter had average permeabilities of 11 darcies and average porosities of 33.5 per cent.

With the limitation that the contact angles and interfacial tensions were static values measured external to the flow models, the following conclusions have been drawn:

1. Wettability in the displacement of oil by water is important in that it determines the manner in which interfacial tension and flood rate affect oil recovery.

2. Oil recovery increases with interfacial tension for water-wet systems and decreases with interfacial tension for oil-wet systems. Neutral wettability systems are less sensitive to interfacial tension than either oil-wet or water-wet cases.

3. For low oil-water viscosity ratios, oil recovery increases with injection rate up to a point where further increase in rate results in no additional oil recovery. Neutral wettability systems stabilize at lower injection rates than either oil-wet or water-wet systems.

4. High viscosity oil systems are characterized by higher oil recoveries at low rather than high flood rates.

5. A procedure has been developed for treating silica sand to produce surfaces of measurable wettability.

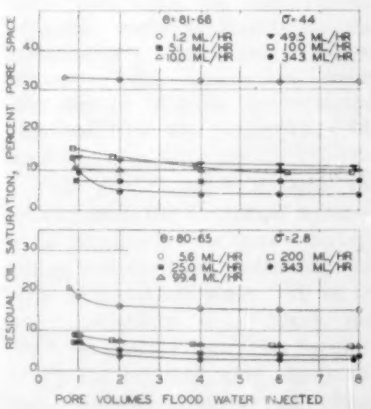

FIG. 5 — EFFECT OF RATE ON OIL RECOVERY FOR FLOODS ON INTERMEDIATE-WET SOLTROL C SYSTEMS.

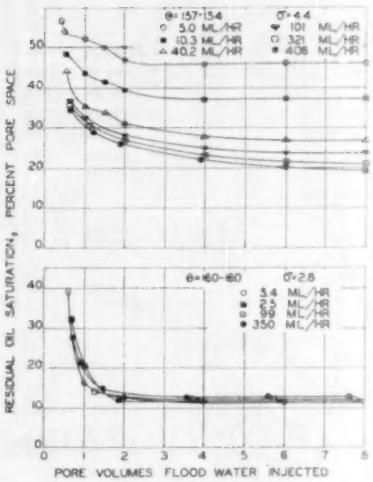

FIG. 6 — EFFECT OF RATE ON OIL RECOVERY FOR FLOODS ON OIL-WET SOLTROL C SYSTEMS.

NOMENCLATURE

σ = Oil-water interfacial tension, dynes/cm.
σ_{so} = Solid-oil interfacial tension, dynes/cm.
σ_{sw} = Solid-water interfacial tension, dynes/cm.
Θ = Contact angle between solid and the water-oil interface measured through the water phase.
P_c = Capillary pressure, dynes/cm².
μ_o = Oil viscosity, cp.
μ_w = Water viscosity, cp.
W_i = Cumulative water injected, pore volumes.
V = Water injection rate, cm³/min/cm².
L = Length of system, cm.
r = Pore radius, cm.
B.T. = Water breakthrough.
A_{sw} = Adhesion tension between solid and water, ergs/cm².
A_{so} = Adhesion tension between solid and oil, ergs/cm².
ΔF = Free energy of displacement of oil by water from a solid surface, ergs/cm².

ACKNOWLEDGMENT

Appreciation is expressed to the Cities Service Research and Development Co. for permission to present this paper.

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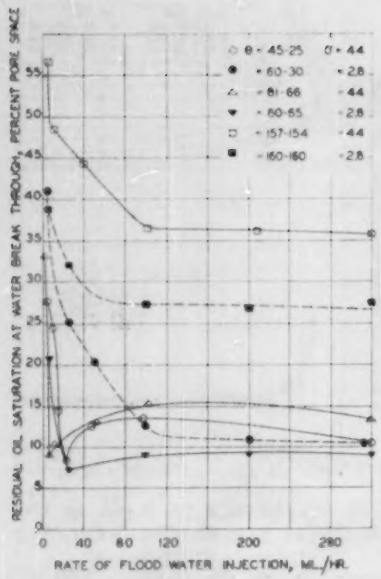

FIG. 7 — EFFECTS OF CONTACT ANGLE, INTERFACIAL TENSION, AND RATE ON OIL RECOVERY AT WATER BREAKTHROUGH FOR FLOODS ON SOLTROL C SYSTEMS.

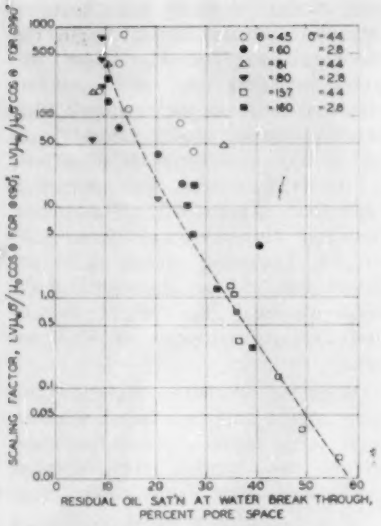

FIG. 8 — RELATION BETWEEN THE GROUP, $LV\mu_w\sigma/\mu_o\cos\theta$ FOR $\theta < 90°$ OR $LV\mu_w/\mu_o\sigma\cos\theta$ FOR $\theta > 90°$, AND OIL RECOVERY AT WATER BREAKTHROUGH FOR SOLTROL C SYSTEMS.

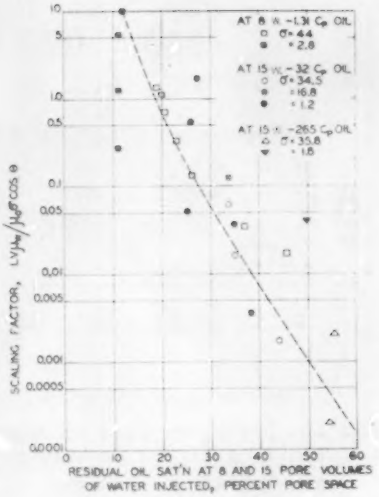

FIG. 9 — RELATION BETWEEN THE GROUP, $LV\mu_w/\mu_o\sigma\cos\theta$ AND OIL RECOVERY FOR 1.0 MG/GM SILICONE TREATED SAND SYSTEMS.

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DISPLACEMENT LOGGING — A NEW EXPLORATORY TOOL

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ABSTRACT

A new electric logging method, called displacement logging, often gives a direct indication of the presence of mobile hydrocarbons in hydrocarbon-bearing formations. This method is based on the detection fluids in these cases. The existwhich is formed between the invading mud filtrate and virgin formation fluids in these cases. The existence of this phenomenon has been verified by laboratory studies and by actual field logs taken in known oil sands.

INTRODUCTION

During the past decade increasing use has been made of conventional electric logs to determine the amount of oil or gas in formations traversed by a borehole. This determination requires knowledge of several factors, such as true resistivity of the formation, formation factor, and water resistivity. Sometimes all of the factors necessary to make a reliable saturation calculation are not available. Also, the computations and corrections which are necessary in such a study often require the services of an experienced log analyst. It has long been the desire of exploration people to have a logging device which will locate hydrocarbon-bearing formations directly without requiring complex interpretation methods. The displacement log, while not completely fulfilling this desire, appears to be a step in that direction.

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Basis for the Device

The basis for this device stems from a phenomenon which occurs when mud filtrate invades a formation which contains displaceable hydrocarbons. As the mud filtrate invades the formation, most of the oil or gas is pushed out of the invaded zone, leaving residual oil. However, in addition to displacing most of the oil or gas, the connate water is also swept out, since the originally irreducible water is mobile in the presence of a water phase.[1,2,3] Consequently, this irreducible water piles up as a bank between the virgin oil zone and the invading filtrate.

If the mud filtrate is of higher resistivity than the formation water—as is commonly the case—the resulting annular zone, containing the bank of formation water, will be of lower resistivity than either the virgin oil-bearing formation resistivity or the invaded zone resistivity. This resistivity configuration, going from high to low to high again as the distance from the borehole increases, is found only in those zones which contain displaceable hydrocarbons. A device which would reliably detect this low resistivity zone would give a direct indication of mobile hydrocarbons.

[1]References given at end of paper.

Illustrations

This phenomenon is illustrated in Fig. 1 and 2. Fig. 1 shows a sketch of a zone containing salty connate water plus displaceable hydrocarbons, along with graphs showing fluid content and electrical resistivity vs distance from the borehole, before invasion occurs. Fig. 2 shows this zone, together with fluid content and resistivity graphs, after invasion by a fresh water mud. The resistivity pattern on moving away from the borehole is high: low: high.

The absence of the low zone phenomenon in water zones is illustrated in Fig. 3 and 4. Fig. 3 shows a sketch of a zone containing salty formation water and residual oil, along with graphs showing fluid content and electrical resistivity vs distance from the borehole, before invasion occurs. Fig. 4 shows this water zone, together with fluid content and resistivity graphs, after invasion by a fresh water mud. In this case the resistivity pattern on moving away from the borehole is high: low since there is no change in water saturation at the head of

the invading front. The same resistivity pattern holds for a 100 per cent water saturated zone.

This low resistivity zone, or "low zone," between the invaded zone and virgin formation then is found only in zones containing displaceable hydrocarbons. It has been studied in detail in the laboratory by core and model studies and has been found to exist in the field in zones which later proved to be productive.

CORE STUDIES

Initial laboratory work was performed to determine the efficiency of fluid displacement in the invaded zone and to determine the resistivity contrast that would exist under various conditions. Fig. 5 shows the resistivity variations along a sand core which had been reduced to connate water by flushing with oil and then flooded with fresh water. The "low zone" phenomenon has been observed in unconsolidated sands, consolidated sand cores, and in both homogeneous and vugular limestone cores.

Resistivity Variation

The resistivity variation in any given case will depend on the water saturation in the virgin formation, the resistivity of the formation water, the resistivity of the invading filtrate, and the residual oil saturation in the invaded and "low zones." The displacement of the connate water by the filtrate is not 100 per cent efficient, so the contrast between the "low zone" and the invaded zone is reduced because of some mixing of the saline and fresh waters. It is believed that in sandstone reservoirs typical resistivity ratios may range between 2:1:10 and 20:3:10 for the invaded zone: "low zone": virgin formation resistivities.

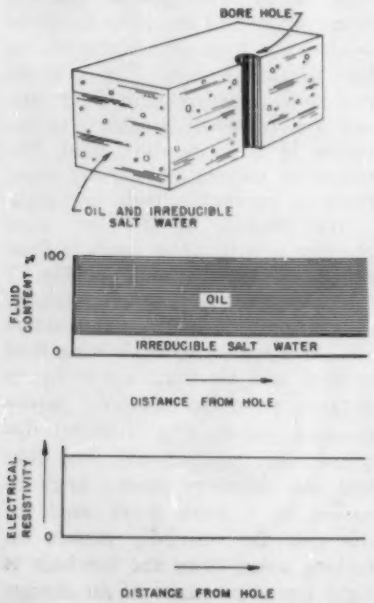

FIG. 1—OIL ZONE BEFORE INVASION.

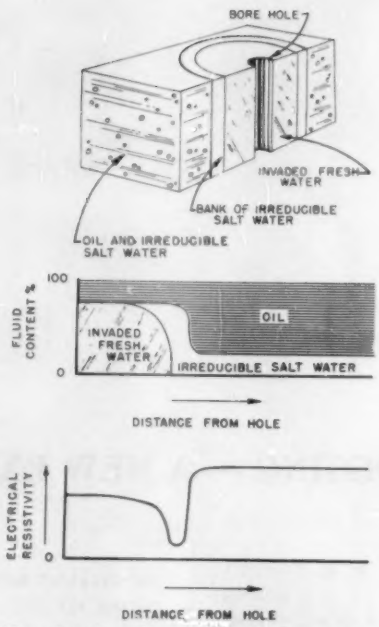

FIG. 2—OIL ZONE AFTER INVASION.

The width of the low resistivity zone depends on the connate water saturation and the depth of invasion. Larger values of connate water saturation and greater depths of invasion lead to wider low resistivity zones. For 20 per cent connate water and five hole diameters invasion, "low zone" widths of about one-half of a hole diameter are believed to exist in sandstone reservoirs.

Stability of Resulting Resistivity Configuration

Another factor that was considered in initial laboratory studies was the stability of the resulting resistivity configuration. Three processes that tend to eliminate the resistivity contrast are: (1) diffusion of the bank of salty formation into the invaded zone, (2) imbibition of the bank of salty formation water into the virgin, oil-bearing formation, and (3) gravitational separation of the three zones due to their different densities.

Limited investigation indicates that unless formation permeabilities are of the order of 1 darcy or higher, the effects due to diffusion and gravitational separation can usually be neglected for periods of several weeks. One test of the stability of the resistivity contrast was made on a 400 md Torpedo sand section, approximately ¼ in. thick, over a period of 13 days. This particular sand was chosen since other data indicated that the imbibition effect would be large. Fig. 5 also shows the change in the resistivity profile due to all causes in the Torpedo sand section. From this we expect a significant resistivity contrast to exist over a period of several weeks after an oil zone is penetrated.

MODEL STUDIED

Electrolytic Wedge Model

After being satisfied that the effect noted in the laboratory appeared promising as a possible means for detecting mobile hydrocarbons directly, attention was directed toward a method of recording the presence of the "low zone" by some type of logging device to be run in the borehole. We have used the term "displacement log" to indicate any logging method which is designed to give an indication of the "low zone" formed due to displacement of oil or gas by mud filtrate. Since, generally, the horizontal depth of investigation of conventional logging arrangements increases with spacing, recording a number of conventional spacings appeared feasible. It was hoped that the resulting profile of apparent resistivity vs spacing would detect the low resistivity zone by showing a minimum. A unique effect in the apparent resistivity profile is deemed necessary since it appears impossible, or at least impractical, to apply reliable corrections to convert the apparent resistivity values to a true resistivity profile.

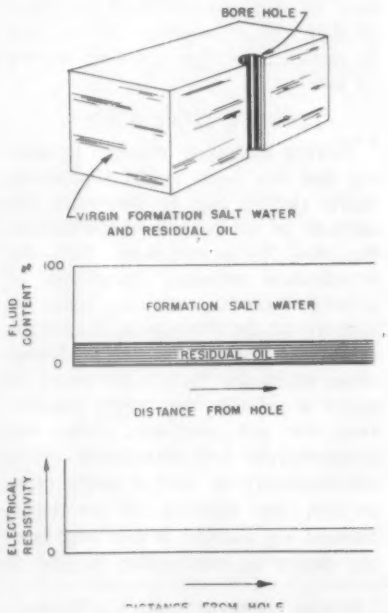

FIG. 3—WATER ZONE BEFORE INVASION.

An electrolytic model was used to simulate a formation with a "low zone." Different salt water solutions and agar mixtures were used to set up the various resistivity configurations desired. A Lucite section was constructed to simulate the logging sonde.

Initial electrolytic model studies conducted with a series of two-electrode spacings did not result in profiles capable of detecting the presence of the "low zones" set up in the model. However, three-electrode spacings did appear to have promise. It was found that in order to detect wide ranges of the resistivity contrast expected in nature, effects due to the flow of current in the mud-filled borehole would have to be reduced or eliminated, if possible. Insertion of a series of insulating discs or bumpers between the logging electrodes accomplished a significant reduction in borehole effects when the bumpers approached 80 to 90 per cent of the borehole diameter.

Much of the early work was done with this electrolytic model. This work indicated that many of the resistivity contrasts expected in nature could be detected with a system of three-electrode spacings employing bumpers. Problems with diffusion between zones of different resistivity in the model and the relative cost of producing a great many model runs led to the use of a resistivity analog model as a more reliable and cheaper method to evaluate the usefulness of various systems for displacement logging.

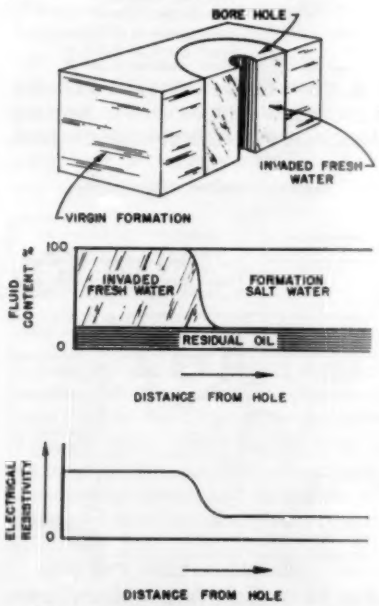

FIG. 4—WATER ZONE AFTER INVASION.

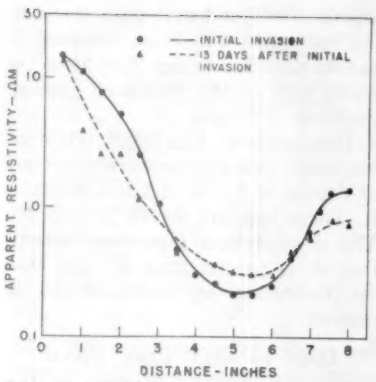

FIG. 5 — RESISTIVITY VS DISTANCE ALONG OIL-BEARING SANDSTONE CORE INVADED BY FRESH WATER.

RESISTIVITY ANALOG MODEL

The analog model used was designed by Hubert Guyod, Houston logging consultant, to simulate earth formations and mud-filled boreholes by means of an electrical resistance network.[4]

Resistance networks were built that would permit various types of displacement logs (apparent resistivity for a given electrode arrangement vs electrode spacing) to be run at different depths in a simulated formation. It was possible to make the runs with insulating bumpers which were 100, 90 and 84 per cent of the borehole diameter.

In the work covered by this paper, the depth reference point is taken as the position of the current or single electrode in a three-electrode arrangement. It was found that this method of presentation resulted in an unique indication of the "low zone." The use of the midpoint of the two potential probes as the depth reference point, as is done in conventional logging, may also be a satisfactory method. The latter method is probably easier to do instrumentally. However, the basic object of displacement logging, detecting the "low zone," remains the same no matter how the data are presented for log interpretation.

In view of all model work to date, we define an indication of the "low zone" to be either (1) a minimum in the graph of apparent resistivity vs electrode spacing which is stationary, i.e., it continues to occur at the same spacing for resistivity profiles run at different depths in the zone being logged; or (2) a stationary inflection in the graph of apparent resistivity vs electrode spacing when the apparent resistivity continues to increase with spacing.

A case is shown in Fig. 6 of a displacement log taken with a three-electrode configuration, at 1-ft intervals opposite a 10-ft thick bed (assuming a hole diameter of 8 in.). The bed of interest has a resistivity contrast of 1:10:1:30 for the mud, invaded zone, "low zone," and virgin formation, respectively. The surrounding bed resistivity, R_s, is equal to three times the mud resistivity. Each profile is plotted with the position of the current electrode as the depth reference point.

It is important to note that the indication due to the "low zone" has the unique characteristic of remaining on the same spacings even while the sonde is moving through the bed of interest. Using the current reference method of plotting, a minimum or inflection due to bed effects would move across the profile as the sonde moved. It is this characteristic that distinguishes the "low zone" indication from any inflection or minimum due to bed boundaries or from layering occurring within a bed.

Over 200 model runs have been made to study the effect of changing bed thicknesses and resistivity contrasts in the invaded zone, "low zone," virgin formation, and adjacent beds using both three-electrode and differential three-electrode configurations.

RESULTS OF MODEL WORK

The results of the model work may be summarized as follows:

1. If an indication of the "low zone" is obtained on a displacement log, it is unique. Bed boundary and layer effects move through the resistivity profile when the sonde moves past the bed.

2. It has not proved possible to date to design a logging system that will detect the "low zone" in all cases. The ability to detect the "low zone" is dependent on the resistivity values of the invaded zone, the "low zone," the virgin formation, and the adjacent formations. It also is dependent on the bumper diameter of the sonde, the thickness of the bed

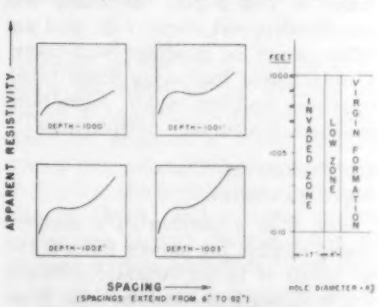

FIG. 6—MODEL RESISTIVITY PROFILES.

of interest, and the type of electrode configurations used.

3. It appears that at least 60 to 70 per cent of producing sand reservoirs can be detected using 90 per cent bumpers. In certain areas the success ratio is expected to be higher, and in others, lower. For limestone reservoirs, model work indicates that detection of the "low zone" will be much more difficult due to the heterogeneous nature of these beds.

FIELD TESTS

A field program undertaken after core studies and early model work proved the existence of the "low zone" in actual wells.

Special Instrumentation

The main problems in special instrumentation were with the physical dimensions of the sonde and the necessary electrical switching that permitted readings to be taken on a plurality of electrode spacings. The electrode sections of the sondes, built for use in 8¾ in. and 9⅞ in. boreholes, were like the sketch shown in Fig. 7. Note that the electrode section of the sonde provides a mud bypass through the center to reduce swabbing effects.

Leaf spring centralizers were used to prevent flexing and excessive wear on the thin rubber bumpers and to prevent excessive scraping of filtercake from the wall of the hole. Inside a pressure tight housing above the electrode arrangement, means were provided to switch the recorder to the appropriate spacing.

Logging Procedures

The initial field tests, run in shallow holes in East Texas, were made by a number of runs past the zone of interest. Each successive run was made with a different spaced three-electrode arrangement.

Later logs were made by stopping the sonde opposite the formation of interest and successively switching the recording device through the various spacings. After all readings were taken at one depth, the sonde was usually dropped about 1 ft, and another series of readings was taken. Displacement logs were often taken opposite uniform shale formations to check instrument performance.

Experimental Data and Discussion

Fig. 8 is a portion of a conventional electric log survey from 5,150 to 5,440 ft in an Atlantic Refining Co. well, Sholem Alechem field, Stephens County, Okla. Fig. 9 shows displacement logs taken opposite a zone which later produced pipe line oil. An indication like those obtained in model runs due to the "low zone" is easily seen in the region of spacing positions 8, 9, and 10.

Displacement logs were taken in the same well opposite a water sand at depths of 5,219, 5,220 and 5,221 ft. These logs are shown in Fig. 10. The displacement logs show clearly that R_i is greater than R_t, and that no indication of hydrocarbons is present.

Logs in Salt Lake Field

Fig. 11 shows a portion of the conventional electric log and micro-device in an Atlantic Refining Co. well, Salt Lake field, Aransas County, Tex. Some displacement logs taken in this section are shown in Fig. 12.

The high resistive streak shown at 7,795 ft on the micro-device moves through the spacings as the depth of the sonde is changed. Any effect due to streaks of different resistivity occurring in the sand will not remain on the same probe readings. It is probable that the displacement logs indicate an inflection in the region of

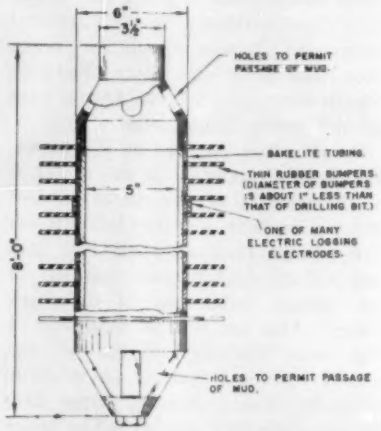
6"
3½
HOLES TO PERMIT PASSAGE OF MUD.
BAKELITE TUBING.
THIN RUBBER BUMPERS (DIAMETER OF BUMPERS IS ABOUT 1" LESS THAN THAT OF DRILLING BIT.)
5"
ONE OF MANY ELECTRIC LOGGING ELECTRODES.
8'-0"
HOLES TO PERMIT PASSAGE OF MUD.

Fig. 7—Displacement Logging Sonde.

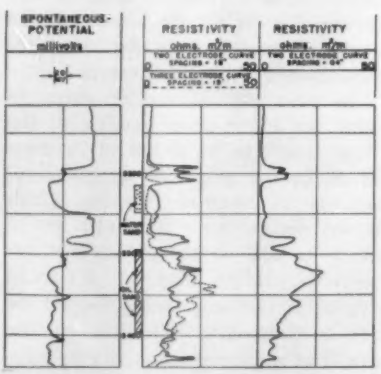

Fig. 8 — Electrical Survey, Atlantic Refining Co. Well, Sholem Alechem Field, Stephens County, Okla.

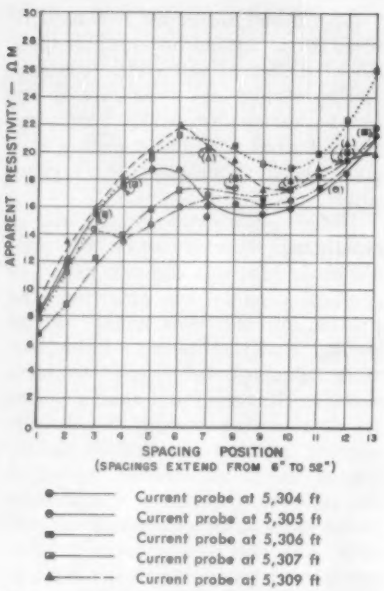
APPARENT RESISTIVITY — Ω.M
SPACING POSITION
(SPACINGS EXTEND FROM 6" TO 52")
Current probe at 5,304 ft
Current probe at 5,305 ft
Current probe at 5,306 ft
Current probe at 5,307 ft
Current probe at 5,309 ft

Fig. 9 — Displacement Logging Results. Well Located in Sholem Alechem Field, Stephens County, Okla.

Remarks: Dips from spacings 8 to 11 indicated movable hydrocarbons. This zone produces clean oil from perforations 5,316 ft to 5,348 ft.

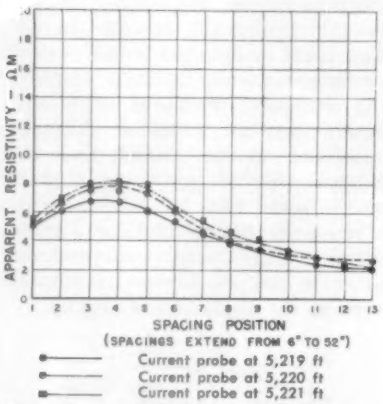
APPARENT RESISTIVITY — Ω.M
SPACING POSITION
(SPACINGS EXTEND FROM 6" TO 52")
Current probe at 5,219 ft
Current probe at 5,220 ft
Current probe at 5,221 ft

Fig. 10 — Displacement Logging Results. Well Located in Sholem Alechem Field, Stephens County, Okla.

Remarks: Indication of a water zone.

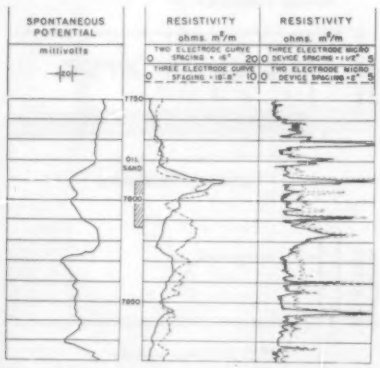

Fig. 11 — Electrical Survey on Atlantic Refining Co. Well, Salt Lake Field, Aransas County, Tex.

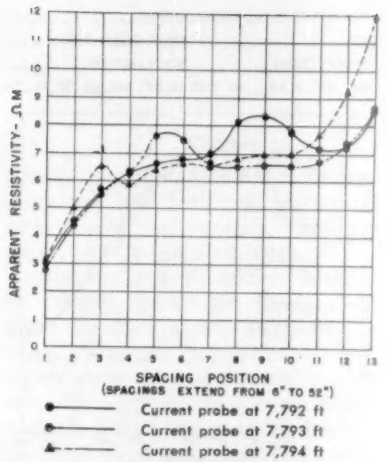
APPARENT RESISTIVITY-Ω M
SPACING POSITION
(SPACINGS EXTEND FROM 6" TO 52")
Current probe at 7,792 ft
Current probe at 7,793 ft
Current probe at 7,794 ft

FIG. 12 — DISPLACEMENT LOGGING RESULTS. WELL LOCATED IN SALT LAKE FIELD, ARANSAS COUNTY, TEX.

Remarks: An indication of oil is noted around spacings 8, 9, and 10. A resistivity streak masks the indication at 7,792 ft. This sand produces in this field.

probe positions 8, 9 and 10. Though it is not the producing sand in this well, this sand produces oil in this field and in this well the sand is above the oil-water contact. Shows in sidewall cores were obtained in this interval.

FIELD RESULTS

To date, displacement logs have been successfully recorded in 10 different Atlantic wells. A total of 120 intervals were logged, 25 of which were in known or probable hydrocarbon-bearing sands. In these hydrocarbon-bearing sands, 19 intervals were interpreted as having an indication due to the "low zone." (Most of the remaining ones were distorted by resistivity inhomogeneities which made interpretation impossible.) Of a total of 88 water formations, or formations of unknown fluid content, which were logged, only four were interpreted as having an indication due to the "low zone." None of these four zones has been tested. No stationary minimum or inflection was found in any shale formation. Table 1 lists these field data.

TABLE 1 — FIELD DATA ON DISPLACEMENT LOGS RECORDED SUCCESSFULLY IN TEN ATLANTIC WELLS

Well	Number Intervals Logged	Known or Probable Oil or Gas Intervals Logged	Known or Probable Oil or Gas Intervals Detected	Shale Intervals Logged, No Indications of Oil or Gas	Water or Unknown Intervals Logged	Presumably Non-hydrocarbon Intervals in Which Oil Was Indicated
1. East Texas	2	1	1	0	1	0
2. Southwest Texas	16	0	0	2	14	0
3. North Louisiana	22	0	0	1	20	1
4. East Texas	12	0	0	0	12	1
5. Oklahoma	20	7	7	0	13	0
6. Southwest Texas	13	6	3	0	7	0
7. Southwest Texas	11	7	5	2	3	1
8. East Texas	6	1	1	1	4	1
9. Southwest Texas	7	3	2	0	4	0
10. Mississippi	11	0	0	1	10	0
TOTALS	120	25	19	7	88	4

It is often difficult to interpret the displacement logs when resistivity inhomogeneities are present. This means that in beds which are not homogeneous over a sufficient thickness to permit reliable interpretation, the displacement logging method is limited.

The field tests have shown that:

1. It is possible to obtain a displacement log under field conditions.
2. Indications are found in hydrocarbon-bearing sands that are similar to those recorded in model setups.
3. Resistivity inhomogeneities make interpretation difficult in many cases.

CONCLUSIONS

The main conclusions reached are as follows:

1. The setting up of the "low zone" is a real phenomenon and the resistivity configuration remains significant over a period of several weeks.
2. The "low zone" causes an unique effect, which can often be detected, on displacement logs.
3. The "low zone" has been detected under field conditions.

We believe that displacement logging is a method which will often indicate the presence of mobile hydrocarbons directly. Such a method should materially aid in the search for oil.

Certain improvements in the displacement logging instrumentation and equipment need to be made, however, before such a method will be practical. An improvement that would permit better discrimination between moving and stationary inflections and minima is the simultaneous recording of the apparent resistivities from different spaced electrode arrangements. A service company has entered an agreement with The Atlantic Refining Co. to develop such a system.

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2. Russell, R. G., Morgan, F., and Muskat, M.: "Some Experiments on the Mobility of Interstitial Water," *Trans.* AIME (1947) **170,** 51.
3. de Witte, L.: "Resistivity and Saturation Distributions in Infiltrated Zones of Porous Formations," *Oil & Gas Jour.* (July 27, 1950) **49,** No. 12, 246.
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DISCUSSION

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MEMBER AIME

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HOUSTON, TEX.

Most of the information supplied in the Martin-Campbell paper is based upon work of The Atlantic Refining group prior to the time a logging system capable of recording simultaneously a multitude of three-electrode resistivity curves was available.

Atlantic's field work, their own model study and that with the Guyod model, indicated that the logical log should consist of a family of about eight three-electrode curves with spacings ranging from 10 in. to 60 in. An instrument to provide such a log has been built.

Fig. 1 shows a block diagram of the system. Two electric fields are established in the formation by constant currents of two different frequencies flowing between the two pairs of current electrodes: $C - C_1$ and $C - C_2$. Each potential electrode disposed along the tool measures potential signals from each of these fields according to the spacing between it and the current electrodes. Thus P_1 receives a signal at 133 cycles per second corresponding to that of a three-electrode configuration of 10 in., and a signal at 200 cycles per second corresponding to that of a three-electrode configuration of 16 in. In a similar manner P_2 receives a signal at 133 cycles per second corresponding to that of a

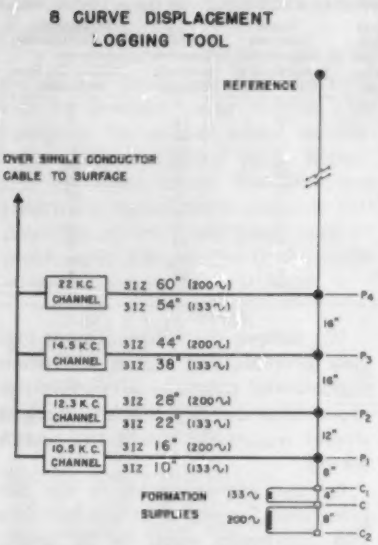

FIG. 1—BLOCK DIAGRAM OF SYSTEM.

three-electrode configuration of 22 in. spacing and a signal at 200 cycles per second corresponding to that of a three-electrode configuration of 28-in. spacing. Similarily, each of the other potential electrodes receives signals corresponding to two three-electrode configurations. The signals picked up by these potential electrodes are used to modulate in frequency various carriers. The carrier signals then are injected into the single conductor line circuit for transmission to the surface. The individual signals are separated there and the log recorded in the conventional fashion.

Fig. 2 shows a portion of a log made with this system recorded on conventional scales. For clarity of the record each of the curves is based at a different vertical rule line. Thus, the 10-in. curve is recorded on a scale of 20 ohm-m with the zero

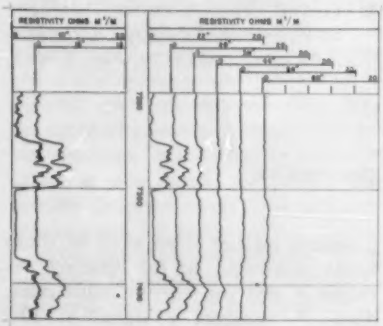

FIG. 2—PORTION OF LOG MADE WITH NEW SYSTEM RECORDED ON CONVENTIONAL SCALES.

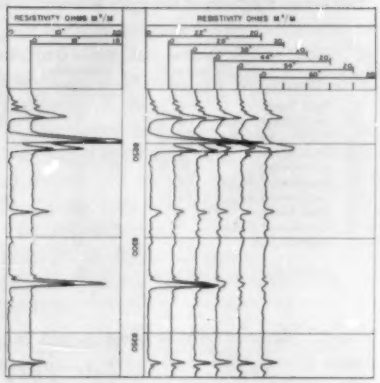

FIG. 3—PORTION OF LOG MADE WITH NEW SYSTEM RECORDED ON CONVENTIONAL SCALES.

at the extreme left vertical rule line. The 16-in. curves, 22-in. curves, etc., are zeroed along the vertical rule lines indicated at the upper part of the figure.

To fully evaluate the displacement concept it is necessary that a plot be made of the resistivity profile as illustrated in Martin's presentation. It is interesting to note, however, how clearly the invasion picture can be shown by this family of three-electrode curves. At the depth of 7,326-51 there is a water sand. The shorter spaced curves are influenced considerably by the invaded zone, while the longer spaced curves are influenced less until at about 48-in. spacing there is no apparent influence.

Fig. 3 shows another section of this same log. Here are included some thin streaks, and a very good presentation is given of the responses of the three-electrode resistivity measuring configurations of different spacings to thin sections. At a depth of 8,365 there is a very thin section and for each spacing the characteristic lag or shadow zone is apparent. At a depth of 8,322 there is a streak of about 4 ft thickness. Here can be noted the characteristic response of the configuration to a bed of critical thickness.

For all evaluations of the displacement logging operations to date it has been necessary to plot the resistivity profile at a given depth for the various spacings. Until recently this plot was made manually. A mechanical reader has been developed which facilitates rapid plotting of the profile directly from the log of the eight three-electrode curves. Fig. 4 and Fig. 5 show such profiles

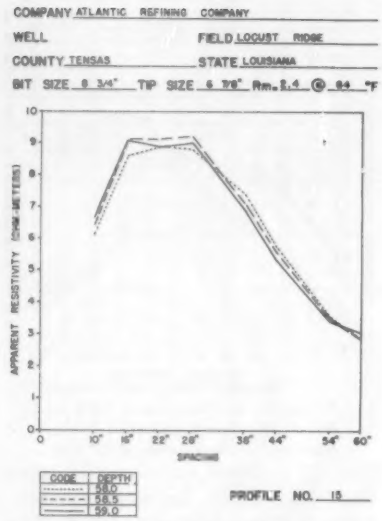

FIG. 4—PROFILES OF A WATER SAND.

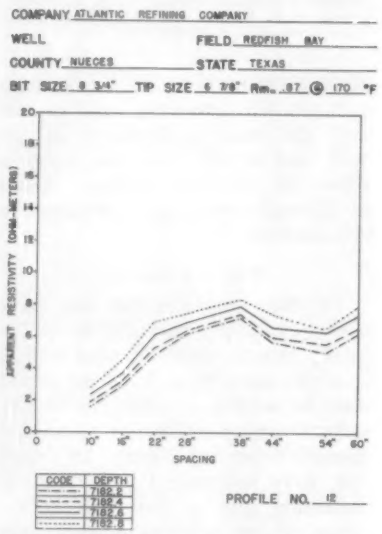

FIG. 5—PROFILES OF AN OIL SAND.

of a water sand and an oil sand respectively. Even with the mechanical reader considerable labor is required to put the data into proper form for final interpretation. It is anticipated that there eventually will be provided an instrument which will automatically plot the profiles as the log is being made so that better well-site interpretations can be made.

To date 13 wells in South Texas, Louisiana and Oklahoma have been surveyed with the fully automatic and simultaneously recording equipment.

Future instruments will provide curves of spacings to 72 in. in a more logical sequence as indicated by past field experience.

DISCUSSION

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MEMBER AIME

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I would like, at the outset, to emphasize that the effect which the authors call the low zone is indeed real. I note this because when the paper was presented verbally, it seemed that many listeners doubted its validity. Data were obtained on water flooding at the Pennsylvania State University just after the war which show the low resistivity zone very strikingly. In these experiments distilled water was used to displace oil from water-wet sands containing both oil and brine. The floods were linear and the resistivity along the direction of flooding was monitored continuously. The build-up of a bank of brine in which the oil saturation was small and, in consequence, the resistivity low, is clearly revealed.

Campbell and Martin are to be congratulated for recognizing that this phenomenon can be applied to the problem of log interpretation. The practical method they suggest of recognizing the low zone is ingenious and, I believe, workable in many instances. Nevertheless, it is my view (necessarily subjective) that the basic approach they propose is anachronistic. The recognition of the low zone, apart from such practical difficulties as stem from equipment and formation heterogeneity (especially interstitial clay), depends upon a reasonable depth of filtrate invasion, a high ratio of R_m to R_w, and adequate hydrocarbon mobility. In many formations, at least with properly tailored mud, these conditions will be met. But this cannot be relied upon. If the method is not universally applicable, its simplicity, instead of being advantageous, becomes the reverse. All sorts of well-meaning log interpretations will inevitably be made by semi-skilled interpreters who are impressed by the simplicity of the low zone technique but unaware of the physical processes on which its validity rests. Mistaken interpretations will be made and these will not necessarily err on the side of optimism. Management will not be impressed.

It may be argued that the low zone technique will supplement other interpretation techniques. This would be admirable but there are already too many logs run. With all due deference to the authors, I subscribe to the following view. The only basis on which log interpretation can rest satisfactorily is one which is universally applicable. This means that directly or indirectly R_t, R_{xo} and the SP must be found (for aqueous-base muds). The resistivity parameters are best measured by focusing logs run in muds whose resistivities are specifically designed to the problems at hand, i.e., maximum R_t likely to be encountered and values of R_m/R_w suited to the logs.

AUTHORS' REPLY to M. R. J. WYLLIE

It seems that M. R. J. Wyllie, though agreeing with the concept of the formation of the low zone, feels that displacement logging is already outmoded. He mentions what he considers to be factors limiting its applicability.

Heterogeneities of the formation, in the form of different resistivity beds, will effect the recognition of the low zone. However, recent field tests show that the displacement log has application in beds of thickness down to 3 or 4 ft. Though we have no field data to prove it, a sand with heterogeneity due to interstitial clay (a shaly or "dirty" sand) may be subject to evaluation with a displacement log. If R_m is greater than R_w in an invaded shaly sand, the resistivity pattern on moving away from the borehole is high:low:high. This is precisely the condition for displacement logging.

It is true that displacement logging must have a reasonable depth of filtrate invasion. Probably just a few inches will do. It is also true that any interpretation method which uses R_{xo} must depend on a few inches filtrate invasion.

A high ratio of R_m *to* R_w is not necessary for displacement logging. When R_m is greater, by any amount, than R_w, the necessary resistivity pattern is set up by invasion of a sand bearing mobile hydrocarbons. If the invaded zone resistivity is less than the true resistivity (with $R_m > R_w$), then we are assured that mobile hydrocarbons are present. Model data indicate that such a resistivity configuration gives the unique inflection necessary for interpretation. This is true even with no low zone as long as the invaded zone resistivity is less than the true resistivity. The fact that the low zone is present accentuates the indication. We do not think that mud resistivity control will be generally necessary. When necessary, it should be no more of a problem than the tailoring of the mud proposed in Wyllie's "universal" method.

As for adequate hydrocarbon mobility, that's what we are looking for. If the oil saturation changes upon invasion from 70 per cent to 40 per cent, we would expect the resistivity of the virgin formation to be about three times that of the low zone. Greater oil saturation changes would give greater contrasts. If the change in oil saturation is much less than 30 per cent, the zone may not be commercial. Zones of this type would also be hard to find with Wyllie's proposed method.

We feel that one of the main advantages of the displacement log method is that interpretations can be made by semi-skilled interpreters. If the unique indication is present, the interpreter is *certain* of movable hydrocarbons in the formation whether or not there is any other supporting evidence, such as "shows." A logging expert can examine zones of possible interest which do not have displacement log indications by conventional interpretation methods. We may say here that the displacement log would permit calculation of values for R_{xo} and R_t. An SP will eventually be run with this device. The bumper sonde serves to an extent the same purpose as the pad on contact logs and the focusing systems in the focused devices used to determine R_t.

Like Wyllie, we too would like to use a method that is "universally applicable." Until such time as one is found, however, we will continue to use any log interpretation method that will aid in the search for movable hydrocarbons. ★★★

Further Discussion of Papers Published in *Transactions*, Volume 204 (1955)

ANALYSIS of RESERVOIR PERFORMANCE K_g/K_o CURVES and a LABORATORY K_g/K_o CURVE MEASURED on a CORE SAMPLE

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(Published as T. P. 4102, Page 128)

DISCUSSION

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MARTIN FELSENTHAL
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The method of comparing laboratory and field performance as set forth by the authors is certainly an interesting and thought provoking approach. The analysis is, however, based on a hypothetical reservoir and data, and we believe one of the basic premises to be in error.

The authors assumed a typical laboratory K_g/K_o curve which was characterized by a critical gas saturation of 10 per cent of pore space. In order to further substantiate the validity of their assumption, the authors cited references which indicate that the critical gas saturation of typical laboratory K_g/K_o curves fall in the general range of 5 to 20 per cent of pore space. This is in disagreement with results obtained in our laboratory.

Results of all our laboratory K_g/K_o tests would lead us to believe that the critical gas saturation is extremely small—less than 2 per cent of pore pace in the majority of cores. The high critical gas saturations reported in the literature are due, we believe, to the inability of many laboratory K_g/K_o procedures to measure gas flow and saturations accurately in the lower ranges. If K_g/K_o data originating at low gas saturations had been used by the authors, it is believed that the conformance of actual and theoretical reservoir performances would have been improved. ★★★

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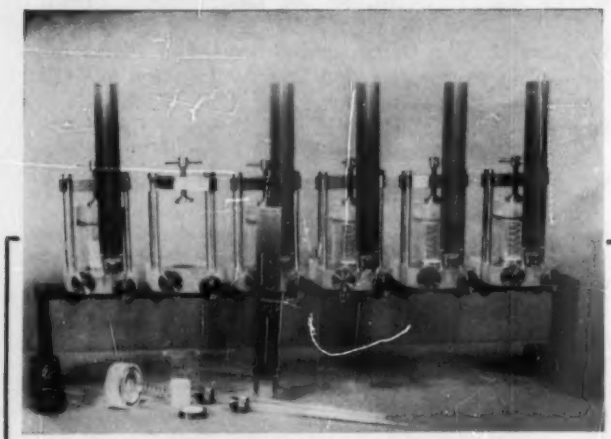

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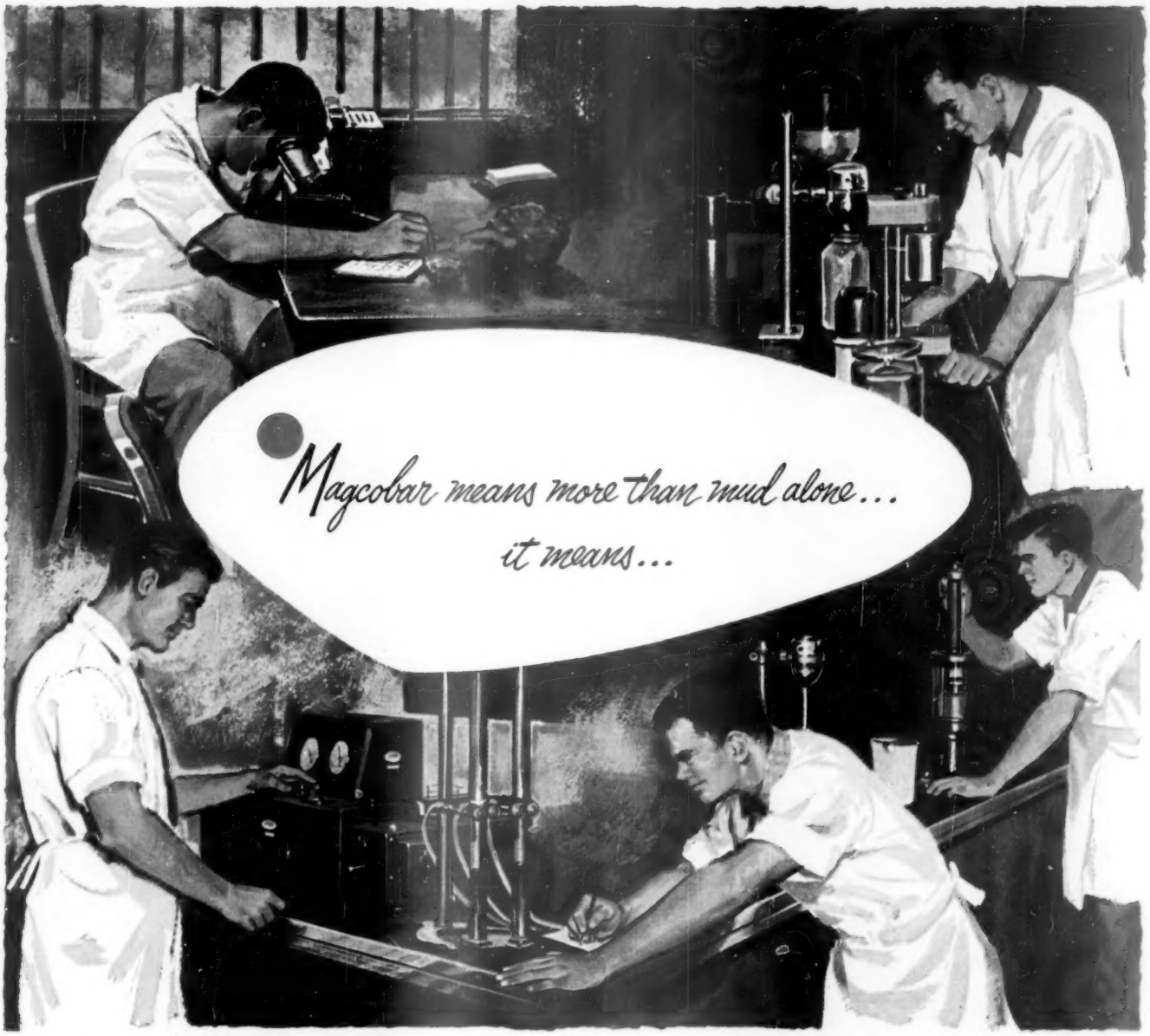

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